Brave New World: Jet Production (and Disappearance) at the LHC Using the ATLAS Detector

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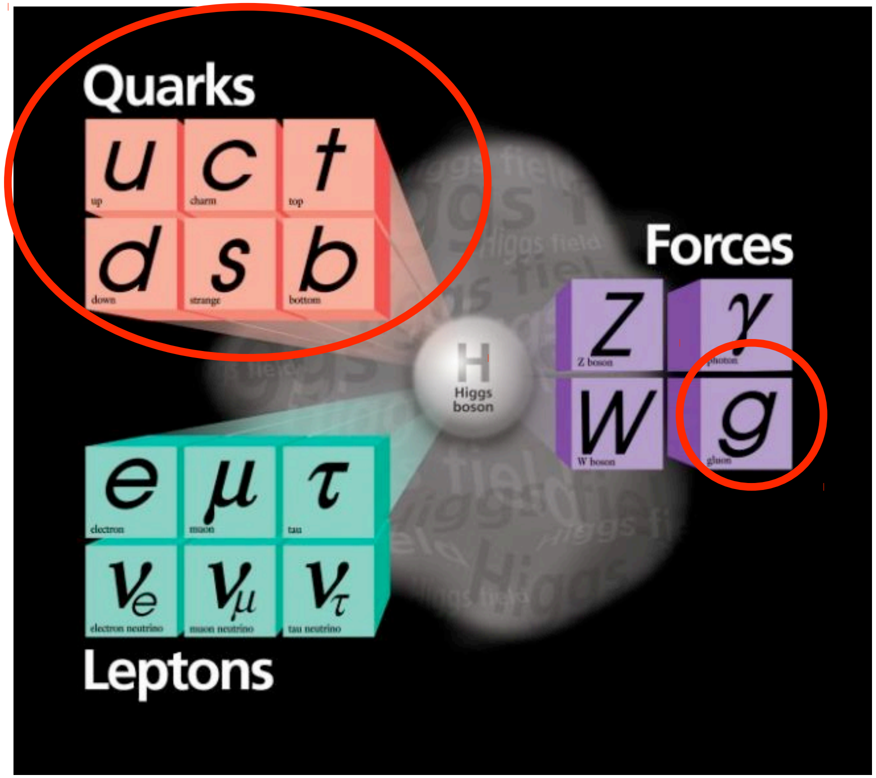
Outline

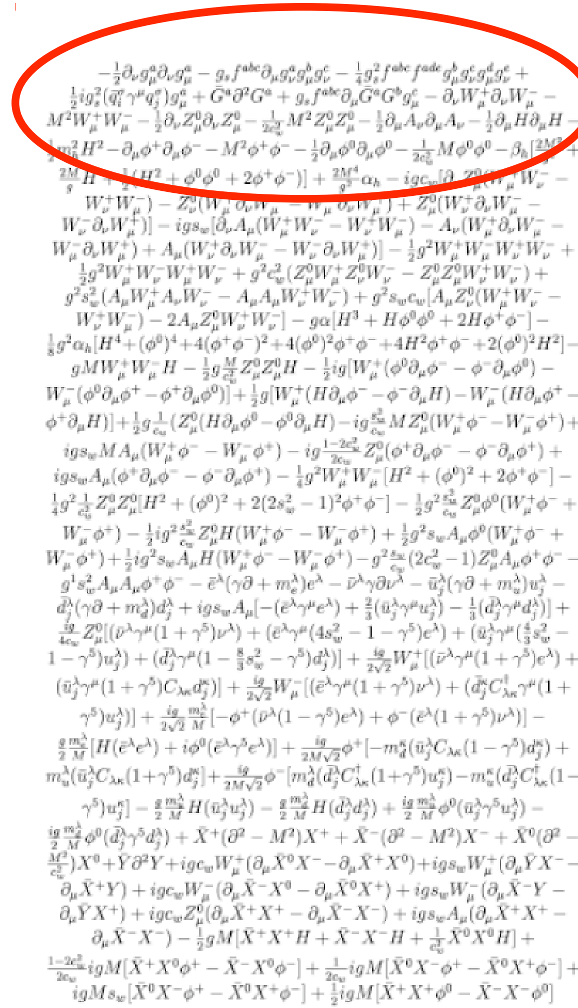
- Introduction to QCD and jet physics
- ATLAS Experiment at the LHC
  - Event displays of interesting jets & dijet events
  - Jet performance and calibration
- Inclusive jet and dijet cross-sections
  - Laboratory for perturbative QCD
- Searches for exotica using dijets
  - Resonances and contact interactions
- Jet quenching in lead ion collisions
- Conclusions and outlook

QCD and jet physics

Introduction

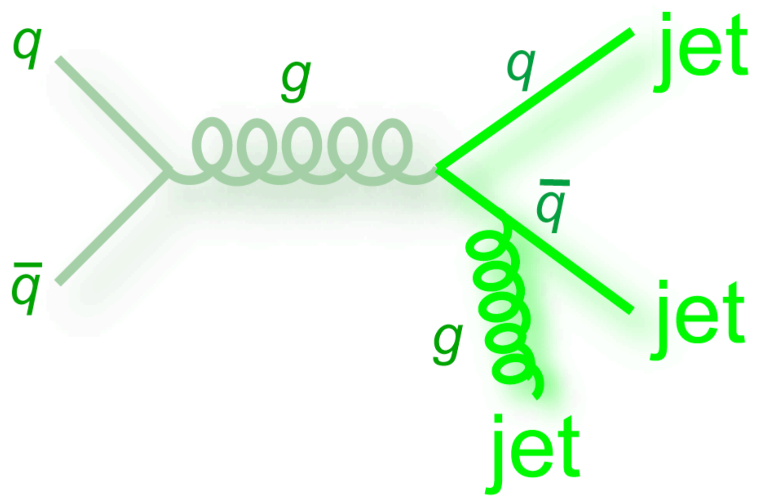
- Quantum chromodynamics (QCD) is the theory of the strong interaction, one of the three fundamental forces in the Standard Model

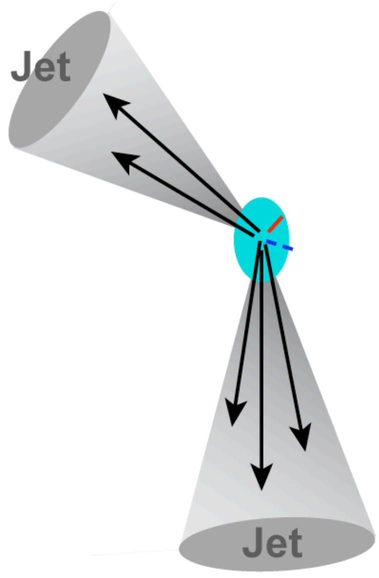




QCD & Jets at the LHC

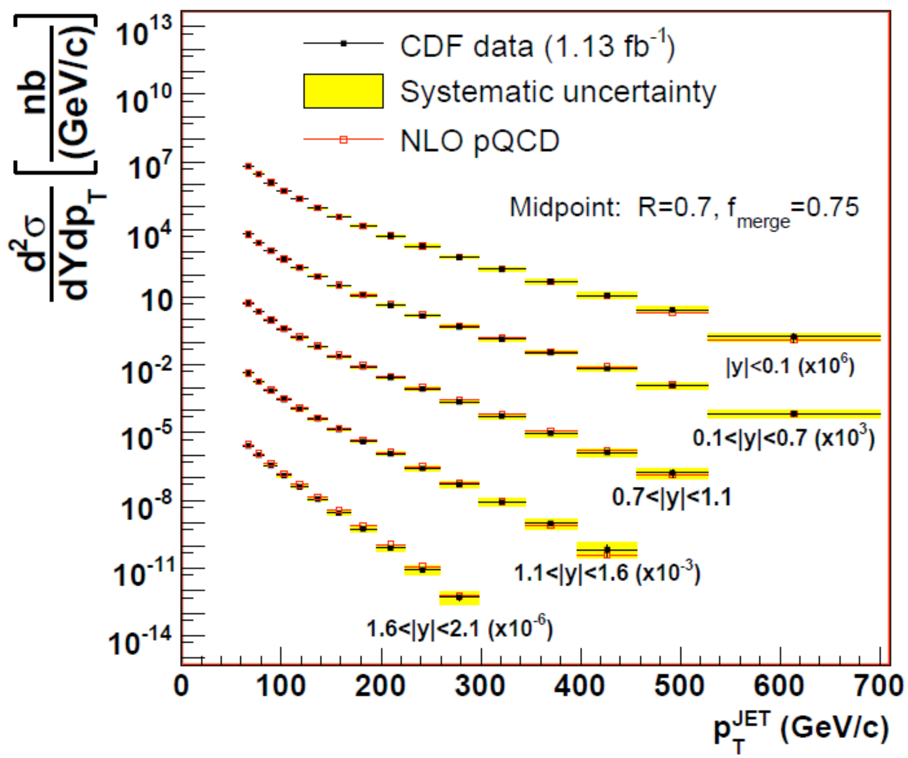
- QCD is ideal candidate for early LHC physics
- Strongly coupled theory → large production cross-sections for jets (collimated flows of hadrons)
- Relatively "simple" final state topologies with close connection to detector performance, e.g. jet calibration
- Tests of Standard Model
  - Probes of NLO perturbative QCD
  - Also sensitive to non-perturbative effects
- Jets are perfect to discover new physics
  - Large production cross-sections and small backgrounds
  - Highest sensitivity to new physics with early data
- Background to many new physics channels

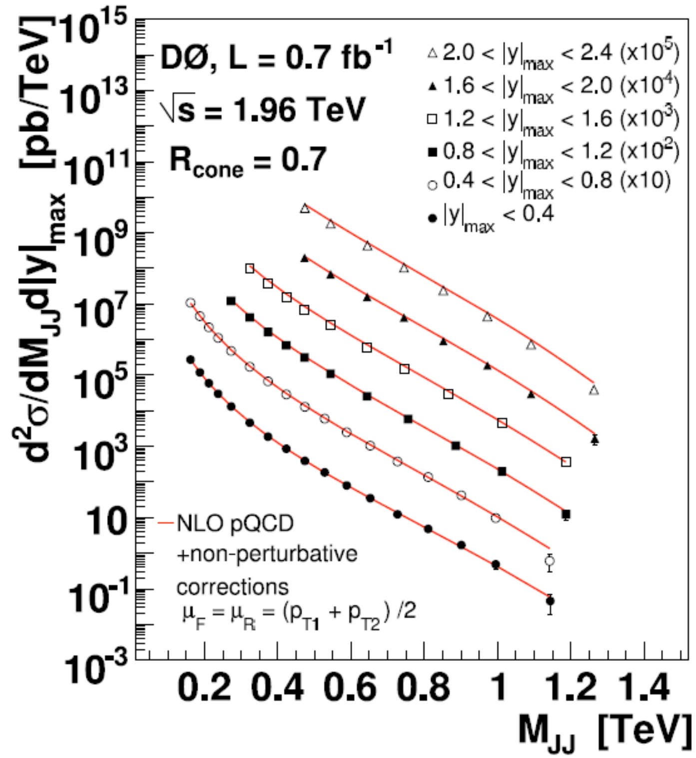




Existing jet measurements

- Many jet measurements using Tevatron ppbar collider at Fermilab
- Inclusive jet pT spectrum extends to p_T of 700 GeV (left: CDF)
- Dijet mass spectrum up to 1.4 TeV (right: D0)

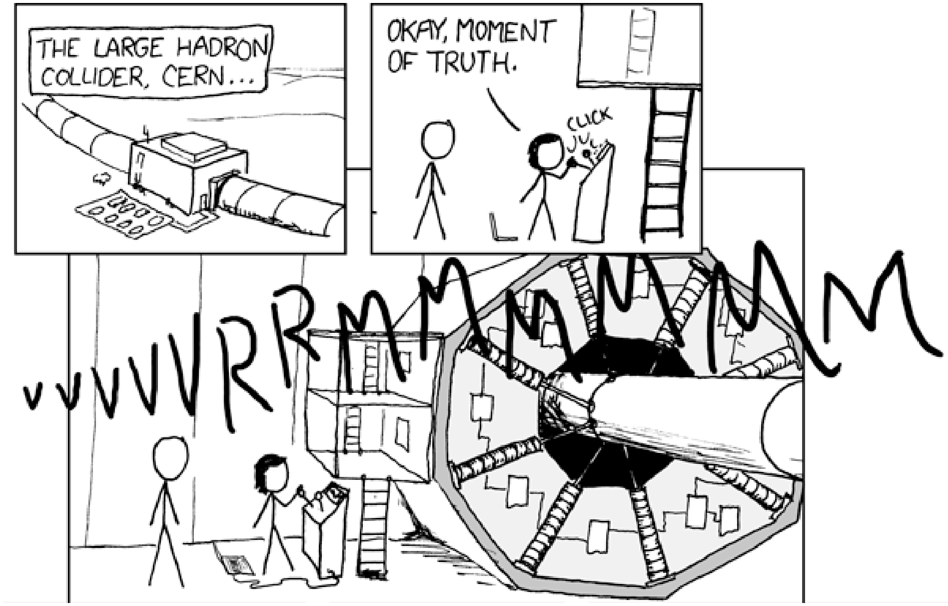


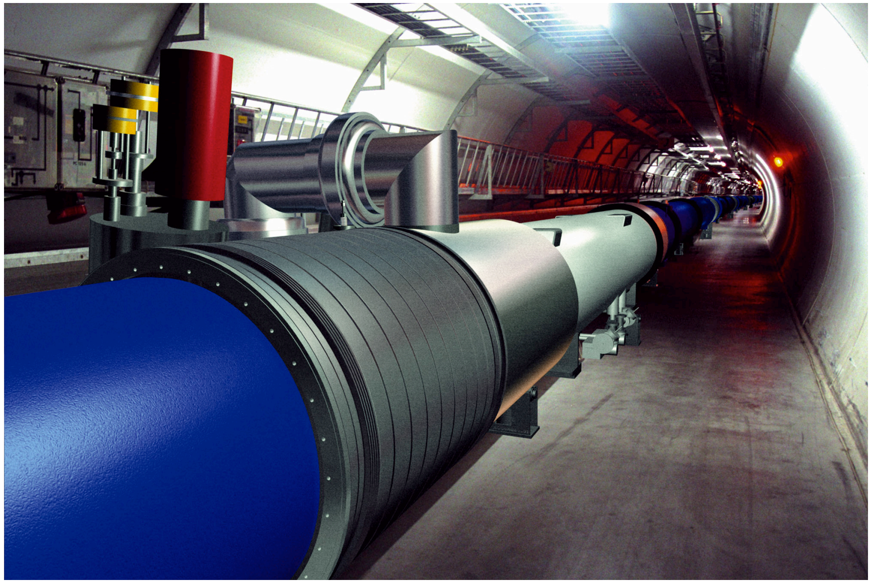


Enter the LHC…

High-p_T jet factory

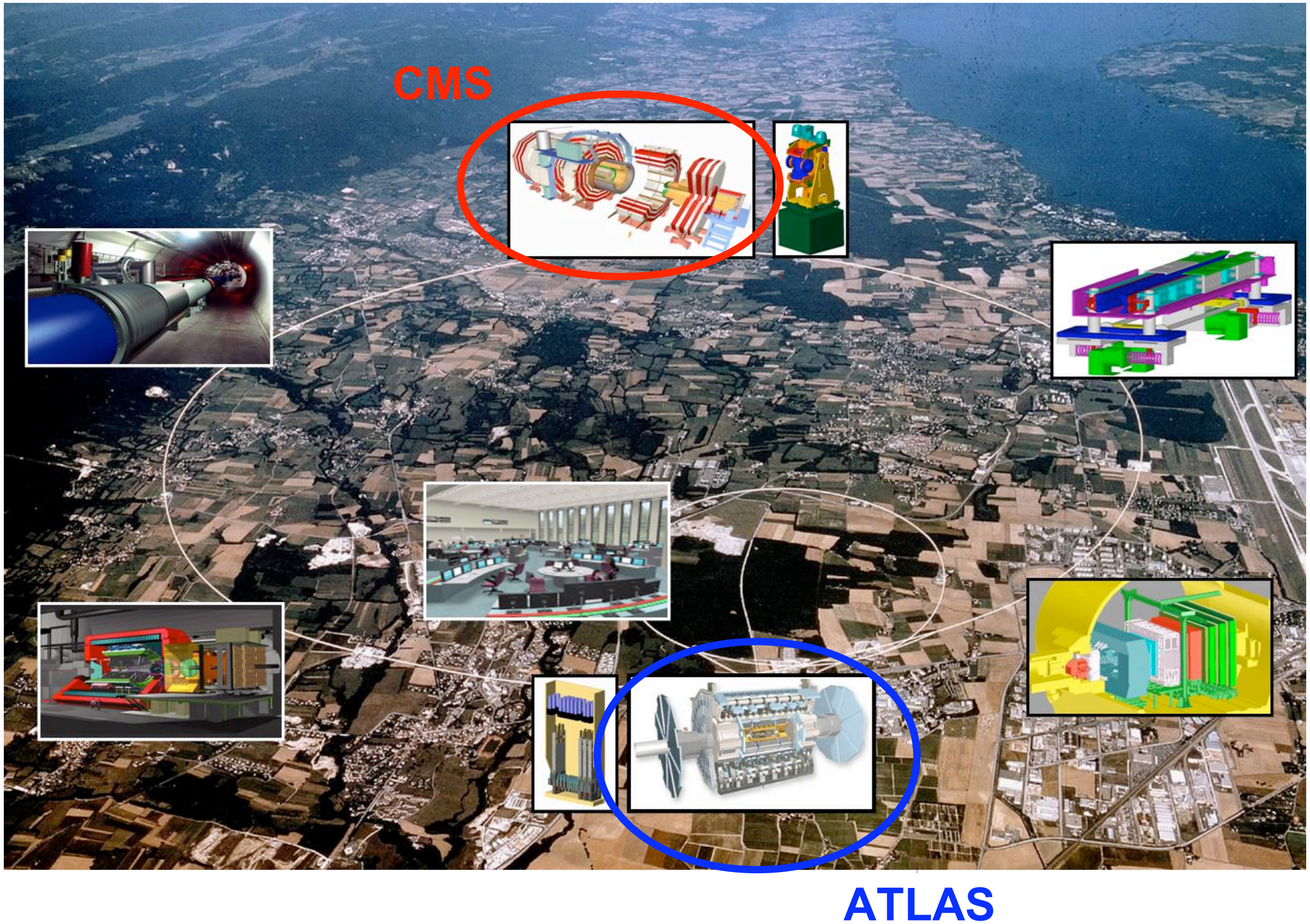
- CERN Large Hadron Collider (LHC) in Geneva, Switzerland has a monopoly on high-p_T jet production
- Highest p_T jets and largest dijet masses ever produced
  - *pp* collisions at sqrt(s) = 7 TeV (design of 14 TeV)
  - 3.5 times larger center-of-mass energy than Tevatron





CERN Large Hadron Collider

- ATLAS and CMS are two general-purpose detectors at the LHC
- Relatively small statistics, but *accelerating* quickly



LHC proton beams at 3.5 TeV

- After initial hiccup during first beam in November 2008, performance of the LHC has been outstanding
  - First collisions at 900 GeV in late 2009
  - Collisions at 7 TeV in early 2010
    - Intense media coverage led to unintended comedy at times

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Large Hardon Collider breaks energy record

The Large Hadron Collider has broken its own record for high energy particle streams.

Published: 12:48PM GMT 19 Mar 2010

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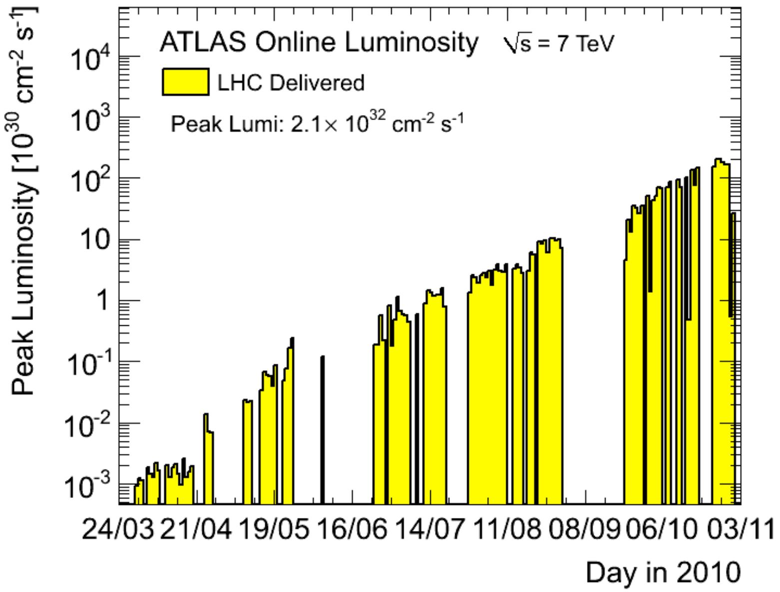
The European Organization for Nuclear Research, or Cern, said beams of protons circulated at 3.5 trillion electron volts in both directions around the 27-kilometre (17-mile) tunnel housing the LHC under the Swiss-French border at Geneva. That is three times more energy than it has ever achieved before.

The next major development is expected in a few days when CERN starts colliding the beams in a new round of research to examine the tiniest particles and forces within the atom in hopes of finding out more about how matter is made up.

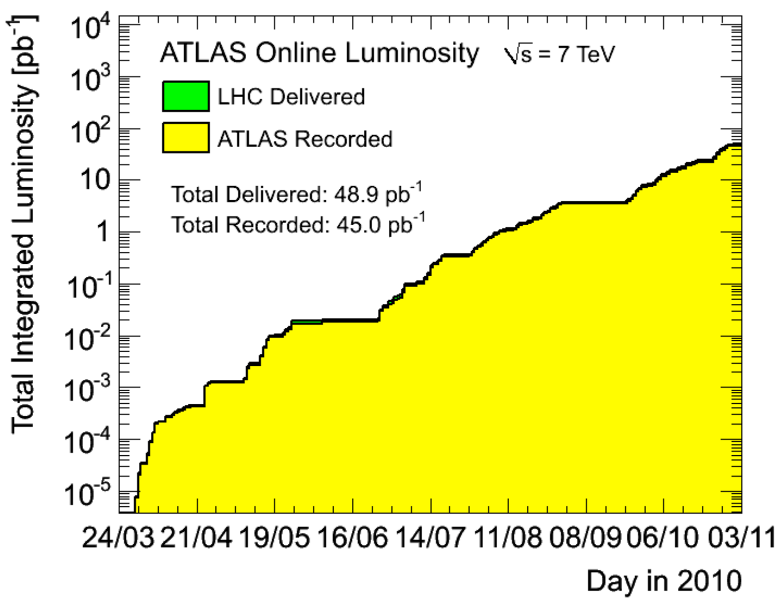
Large Hadron Collider

Luminosity of the machine

- Instantaneous luminosity increased by 5 orders of magnitude since March
  - Peak instantaneous luminosity in 2010 = $2.1 \times 10^{32}\ cm^{-2}\ s^{-1}$



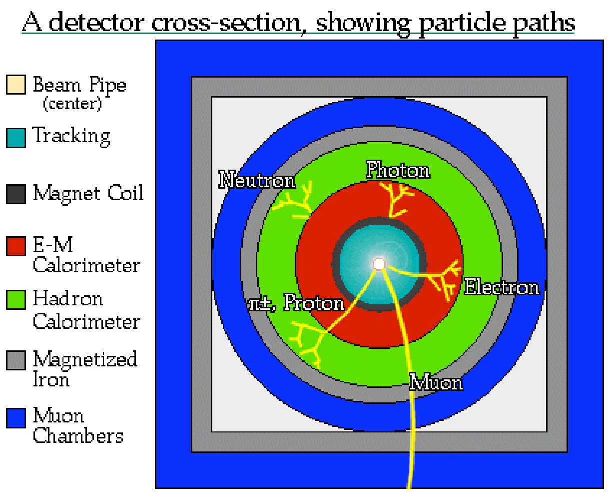
- Dataset
  - ICHEP (July): 17 nb^{-1}
  - These results: 3 pb^{-1}
  - Full 2010 dataset (Winter): 45 pb^{-1}

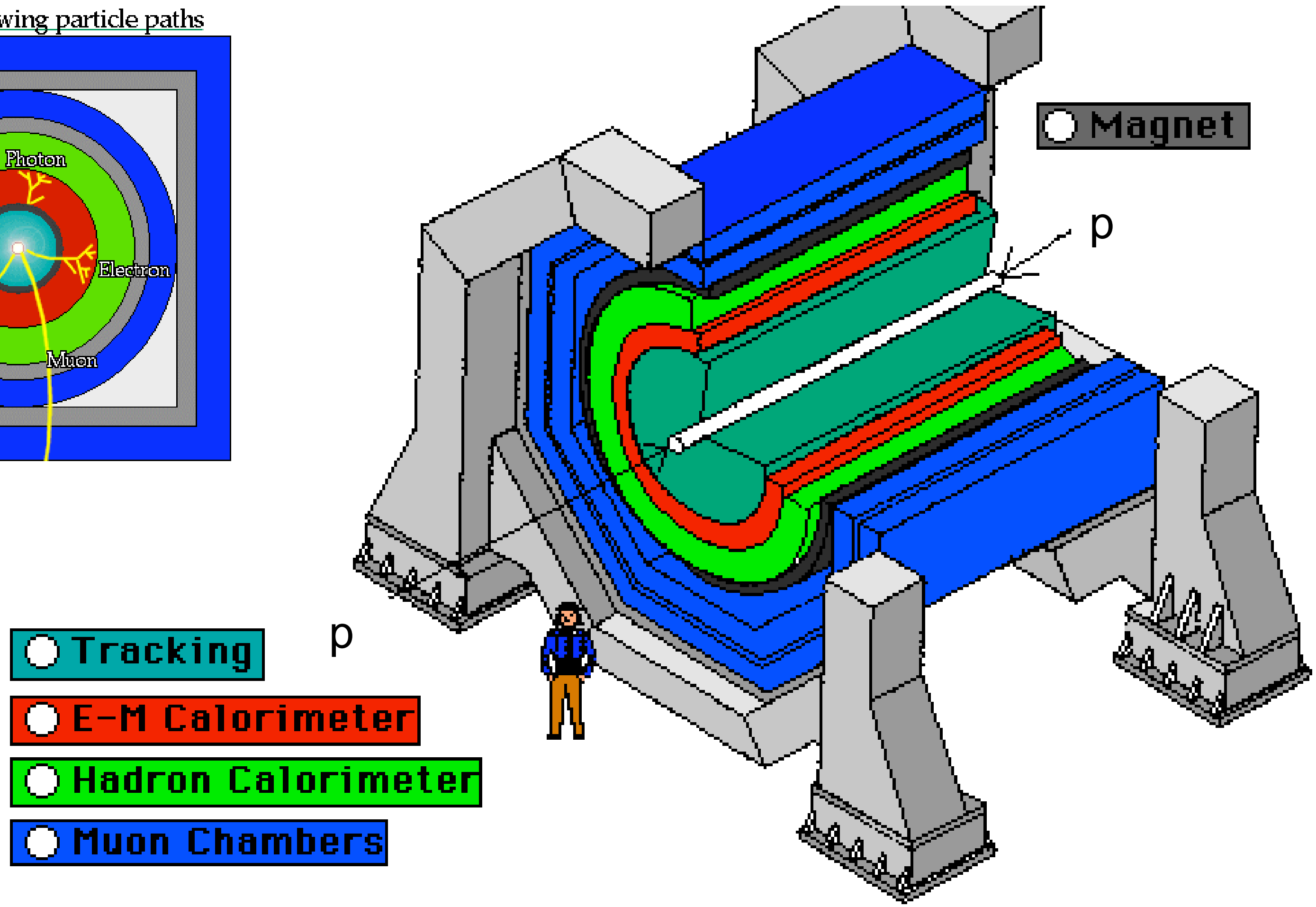


The ATLAS experiment

ATLAS Detector (schematic)

- Schematic of a general-purpose detector



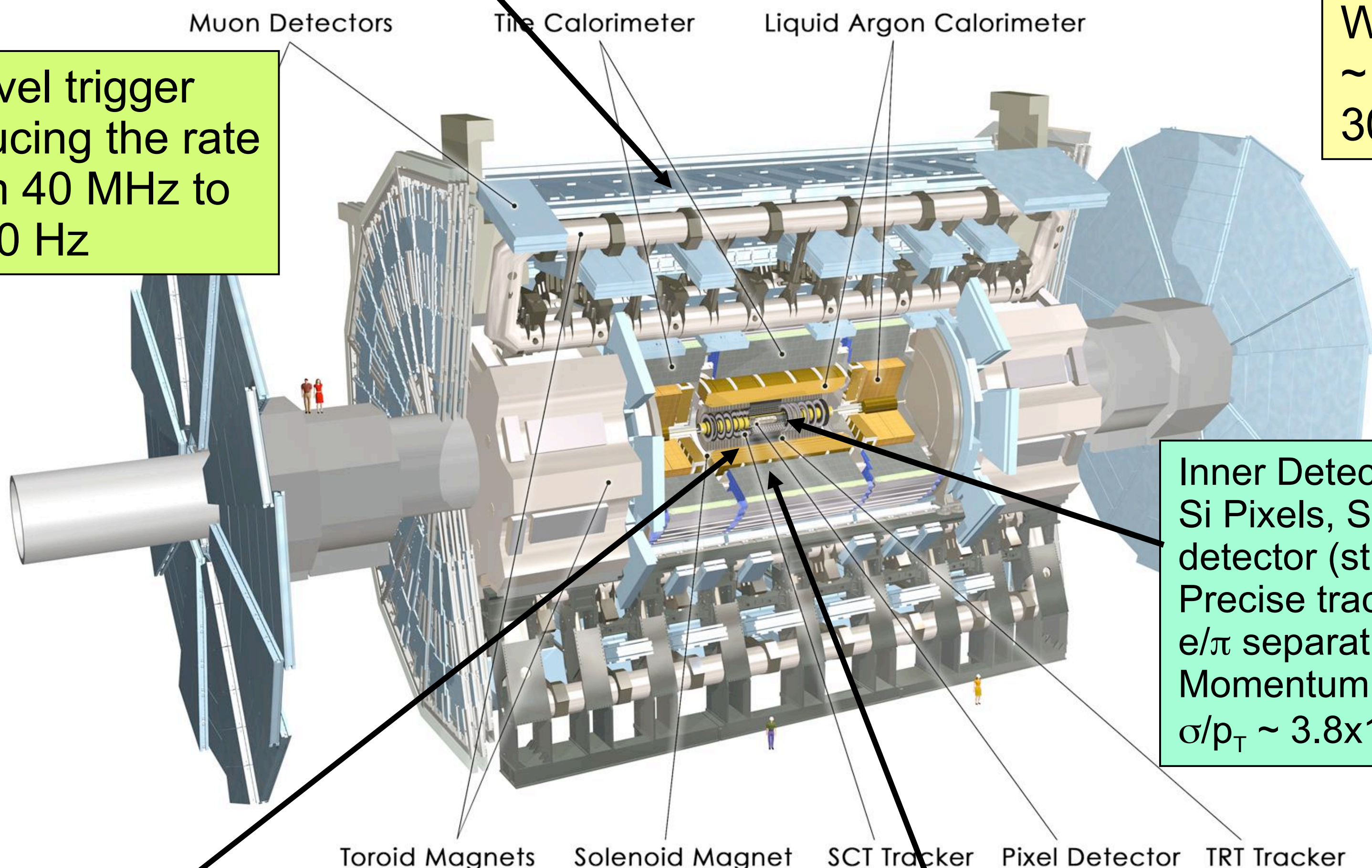


Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

ATLAS Detector

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz

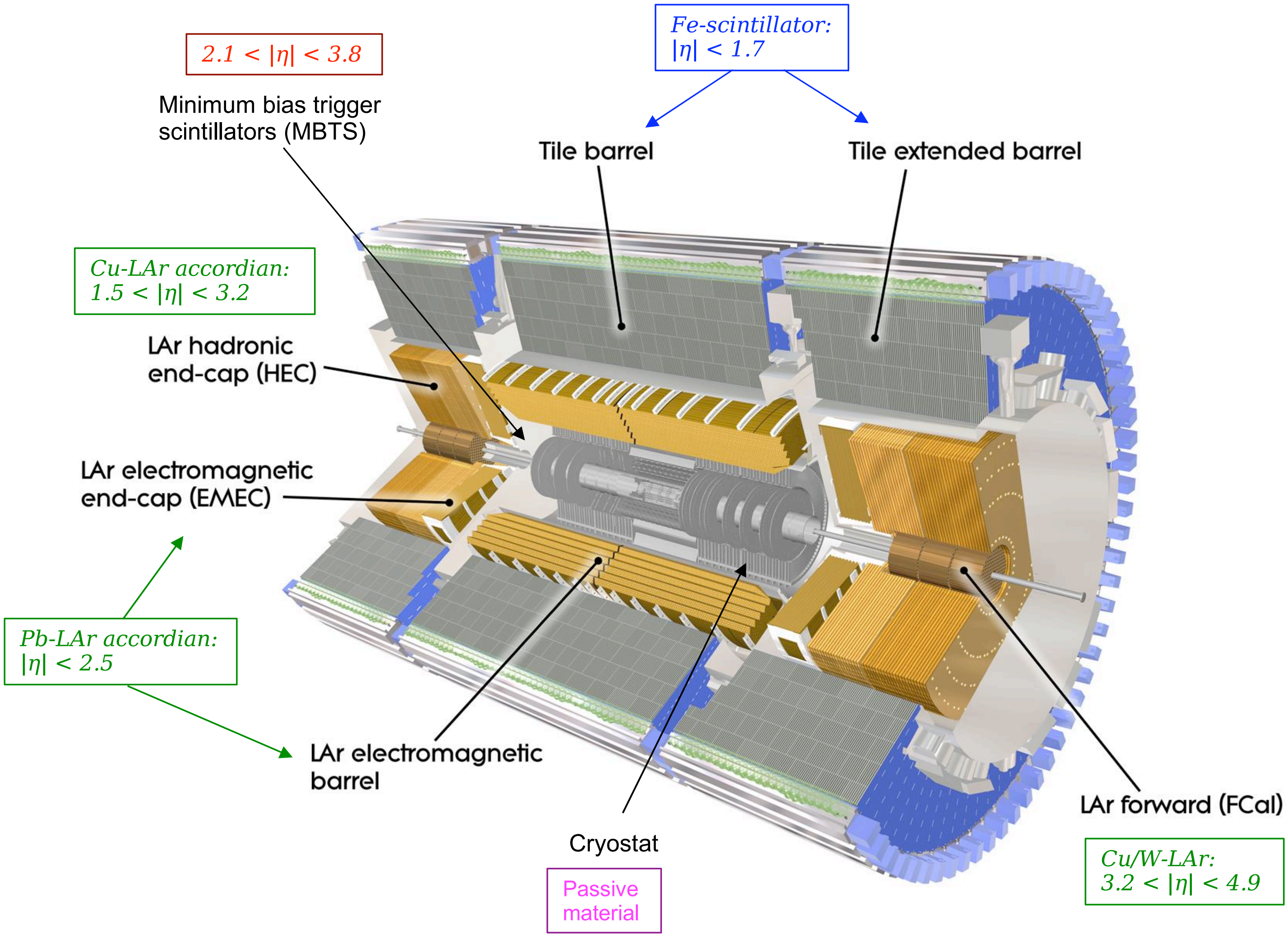


Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

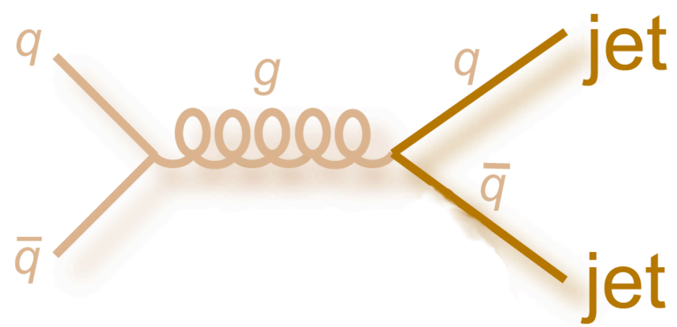
HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

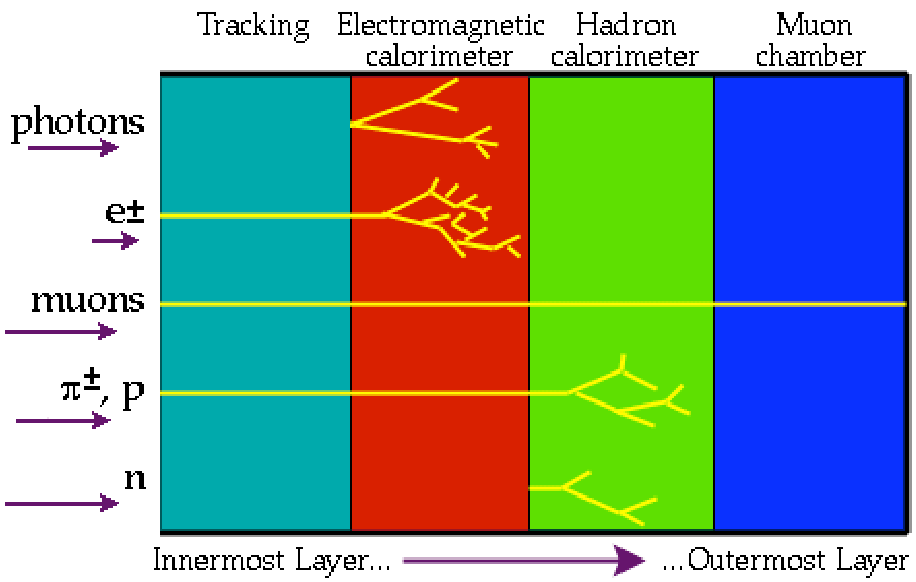
ATLAS Calorimeter



Inclusive jet production

- Leading order diagram in SM is dijet production
  - Deposits energy primarily in hadronic calorimeter
- Define jets inclusively as: "calorimeter energy deposition"
  - Backgrounds from electrons, photons, etc are negligible because QCD cross-sections are so large





“QCD in Year One”: Then and Now

- At the ATLAS Workshop of the Americas at NYU in 2009, I described in the QCD plenary the various jet measurements we expected to make with the first year of data.
- After ~8 months of *pp* collisions at 7 TeV, where do we stand now?
  - Inclusive jet p_T ⊠
  - Dijet mass spectrum ⊠
  - Dijet χ angular distribution ⊠
  - Dijet $\Delta\varphi$ decorrelation ⊠
  - Dijets with rapidity gaps ⊠
  - Multi-jets ⊠
  - W/Z + jets ⊠
  - Jet shapes ⊠
  - Searches for exotica ⊠
  - Plus a bonus (jet quenching) in lead ion collisions! ⊠

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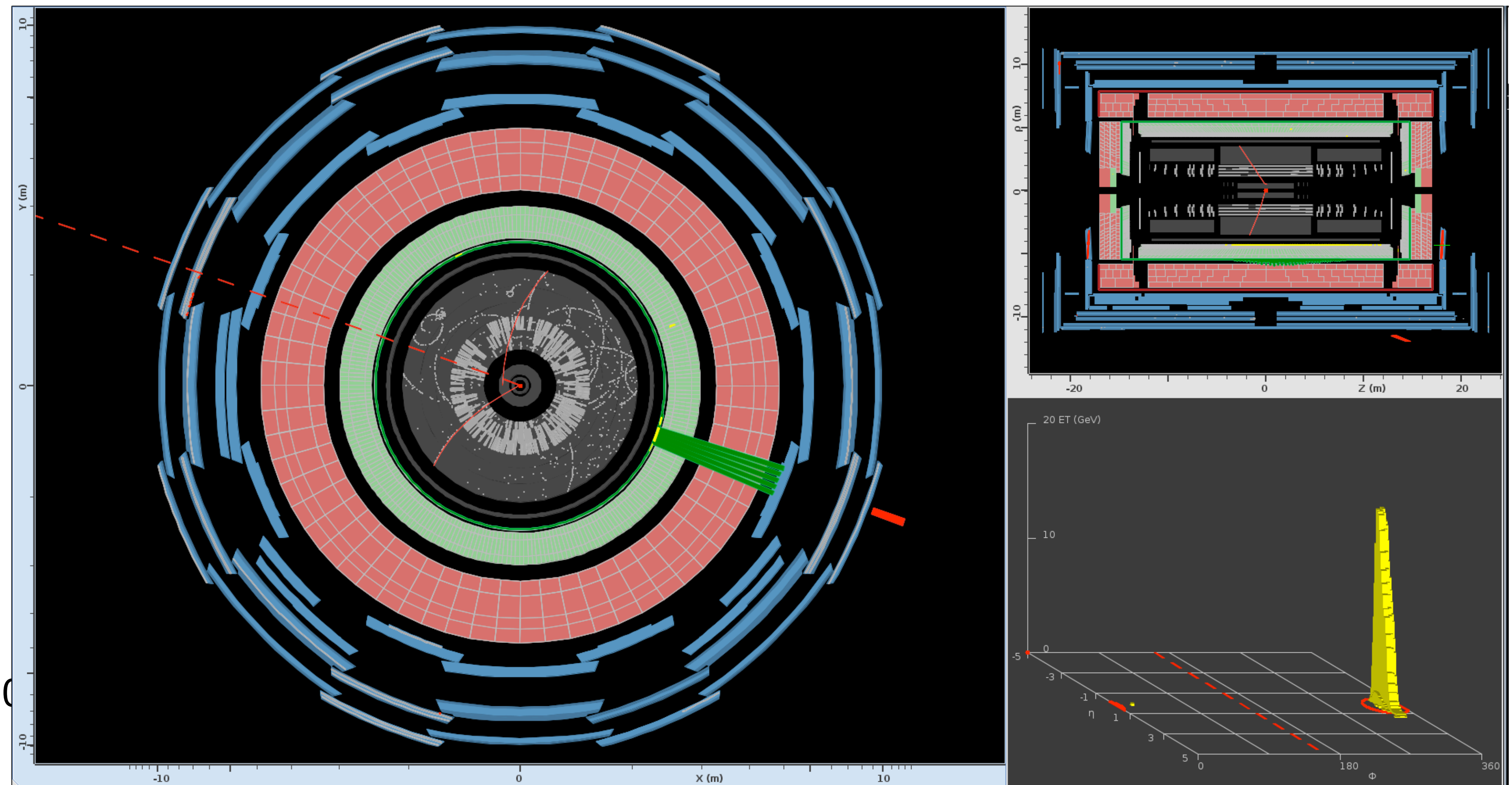
  - **Plus a bonus (jet quenching) in lead ion collisions!** ⊠

Will focus on these analyses today

What do jets look like in the ATLAS calorimeter?

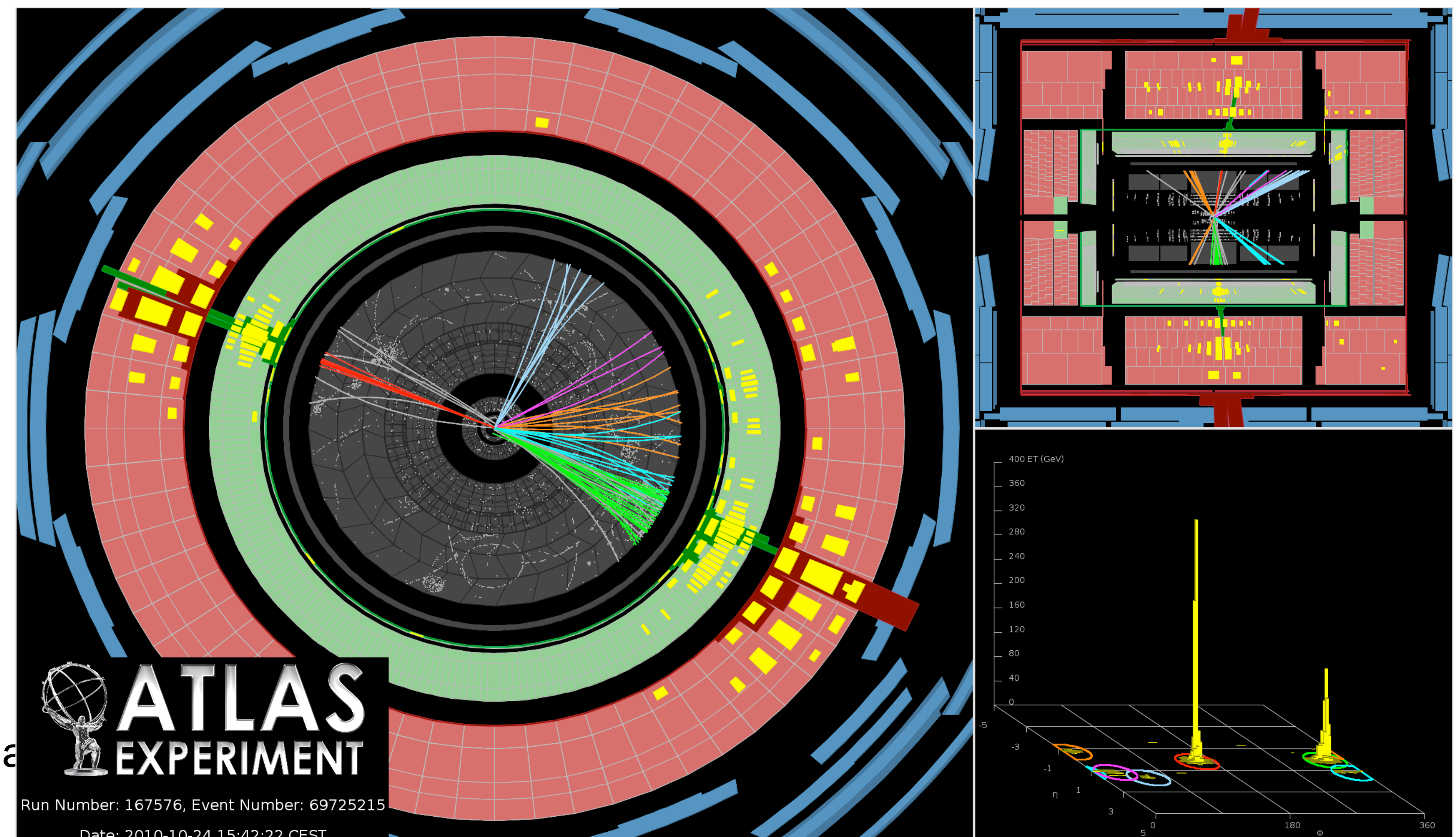
What a high p_T jet does NOT look like

- ***Fake*** jet with p_T of 1.1 TeV
  - Beam halo particle showers longitudinally in EM presampler so its energy receives large weight
- Missing ET = 1.3 TeV (exactly opposite in φ to leading jet)
- Add jet cleaning cuts to reject fake jets like this



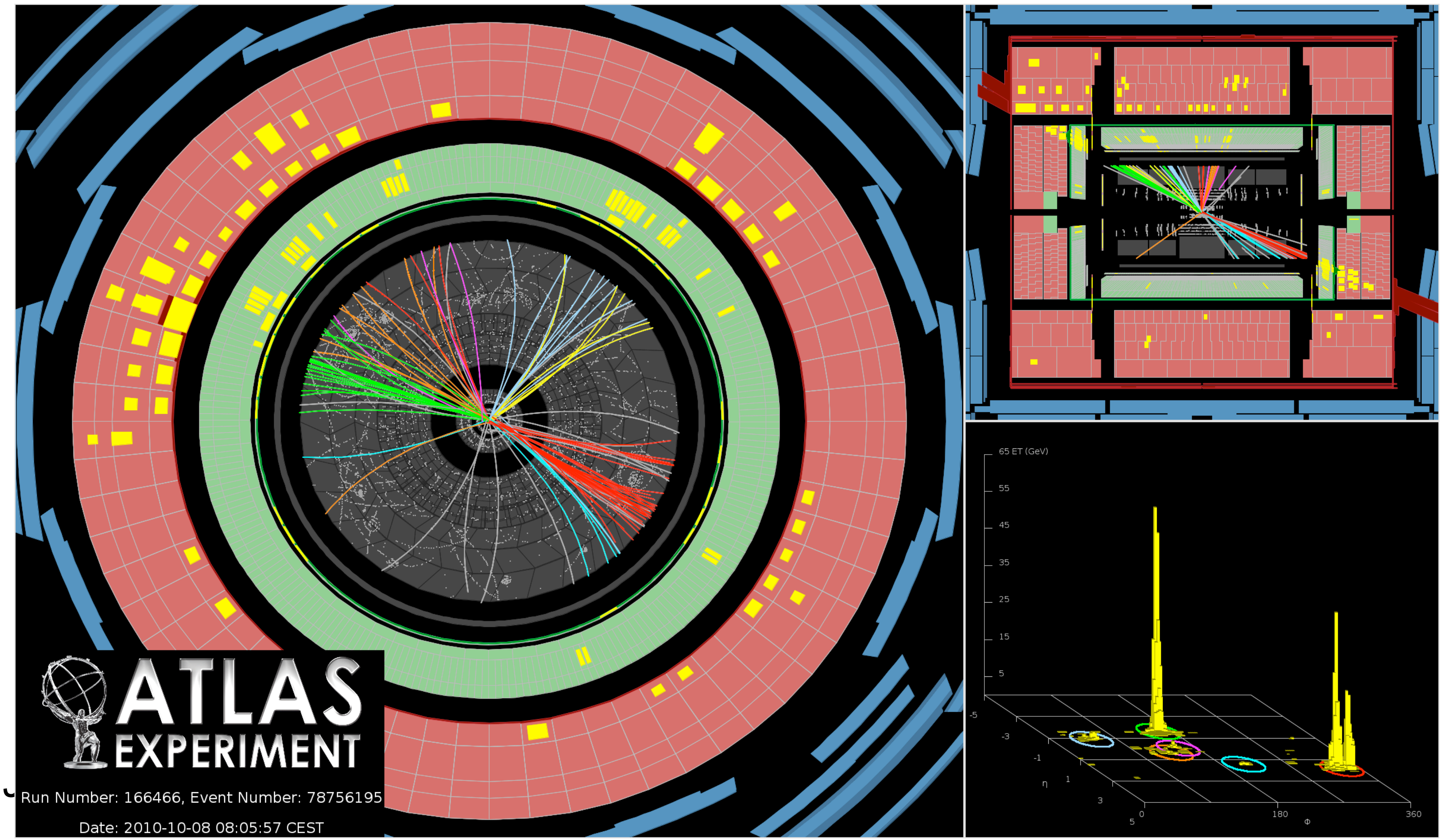
High p_T jet (1.3 TeV) and large central dijet mass (2.6 TeV)

- Two central, well-measured jets in |y|<0.8 with very high-p_T
  - 1st jet: pT = 1.3 TeV, η = 0.2, φ = 2.8
  - 2nd jet: pT = 1.2 TeV, η = 0.0, φ = -0.5
- These events are the most interesting because they have large momentum transfer and s-channel is more sensitive to new physics



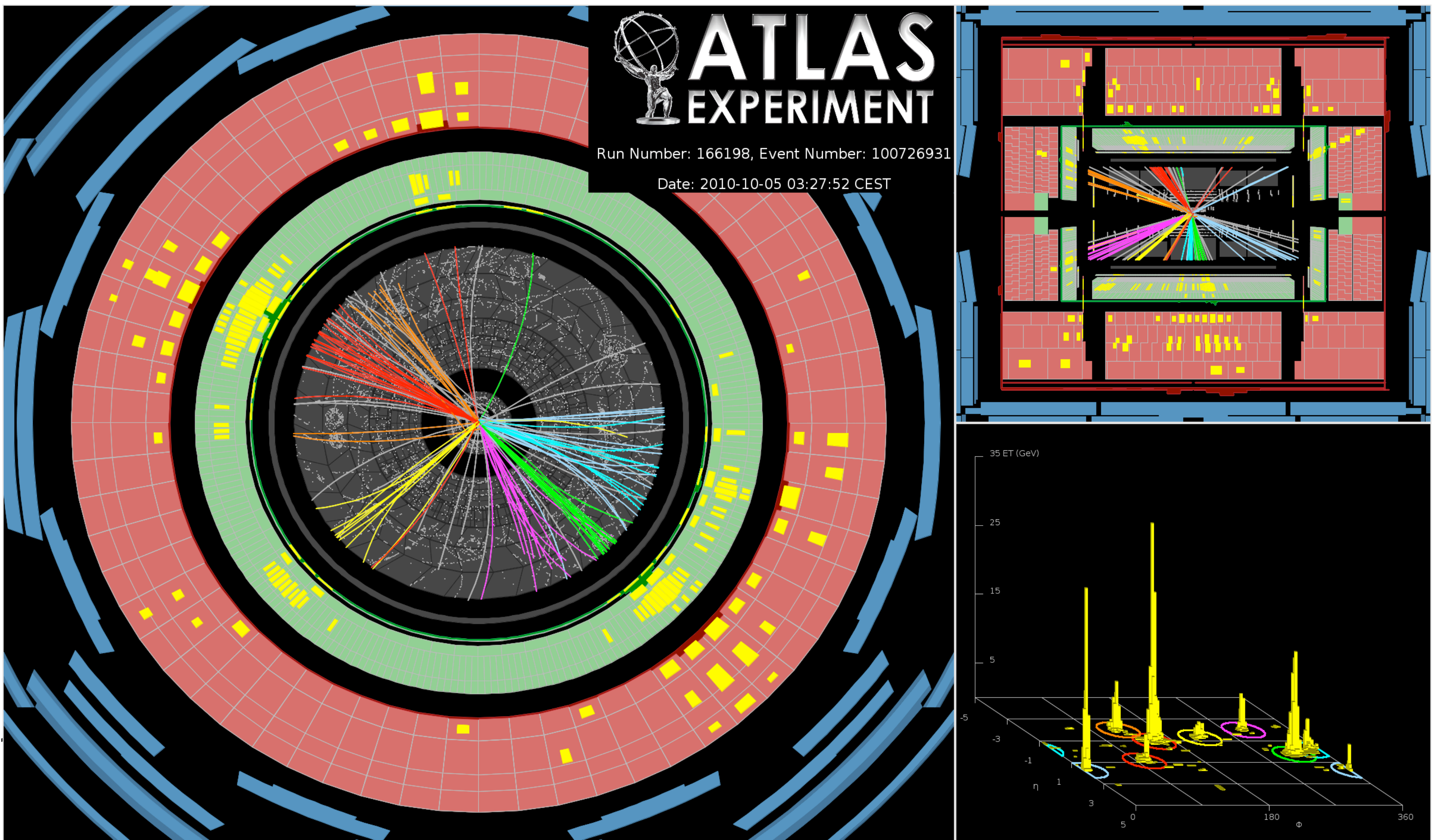
Large dijet mass (3.7 TeV)

- Dijet mass generated by rapidity separation of forward jets
  - 1st jet: pT = 670 GeV, η = 1.9, φ = -0.5
  - 2nd jet: pT = 610 GeV, η = -1.6, φ = 2.8
- Characteristic of t-channel and u-channel scattering in QCD



High jet multiplicity event
(8 jets above pT = 60 GeV)

- Eight jets between 60-300 GeV (associated to single primary vertex)
  - 1st jet: p_T = 290 GeV, η = -0.9, φ = 2.7
  - 2nd jet: p_T = 220 GeV, η = 0.3, φ = -0.7
- Exemplifies large amount of gluon radiation



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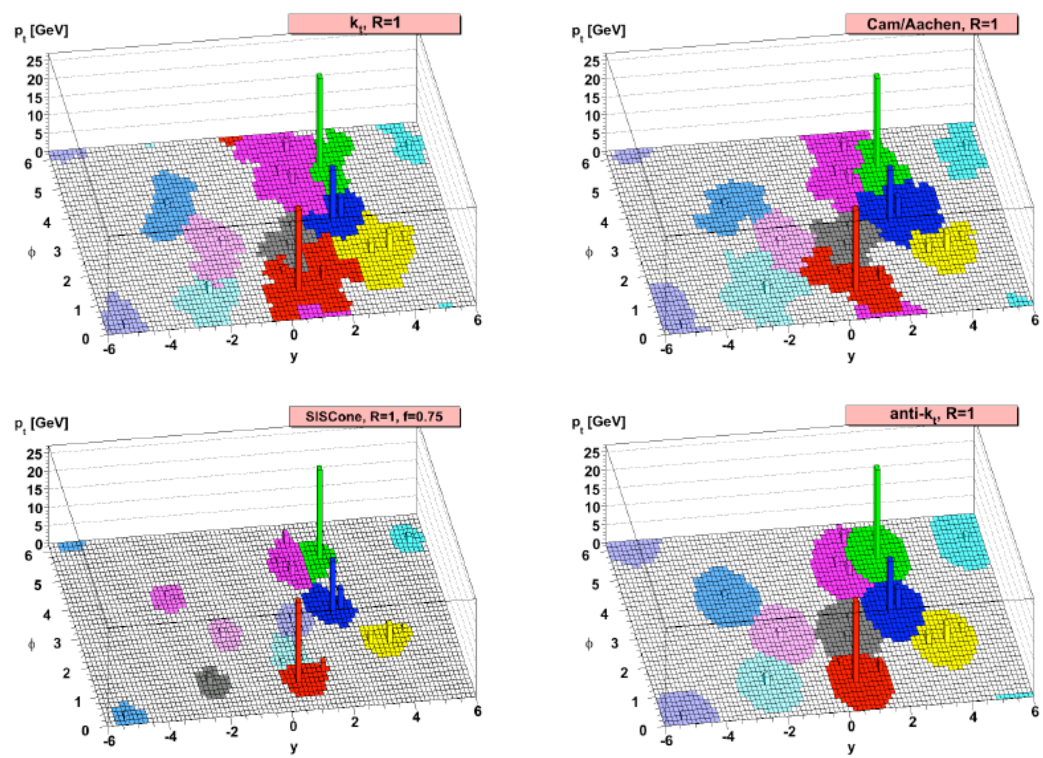
Jet trigger, reconstruction, selection, and calibration

Jet reconstruction

- Jets reconstructed offline from calorimeter energy clusters using anti-k_T jet algorithm with clustering parameter R=0.6
  - Topological clusters are formed from seeds of calorimeter cells above noise thresholds to reject noise
    - Iteratively add neighbors farther away
  - Anti-k_T is an infrared and collinear safe jet algorithm
    - Stable against underlying event and pileup
    - Uniform, cone-like jets



Jet trigger & reconstruction

- Require jet trigger fired
  - Trigger uses simpler and faster algorithms than offline reconstruction
- Lowest threshold jet trigger efficiency (left) is above 99% for p_T > 60 GeV
- Jet reconstruction efficiency (center) & purity (right) are each above 99% for p_T > 30 GeV

→ Restrict leading (sub-leading) jet to p_T>60 GeV (30 GeV)

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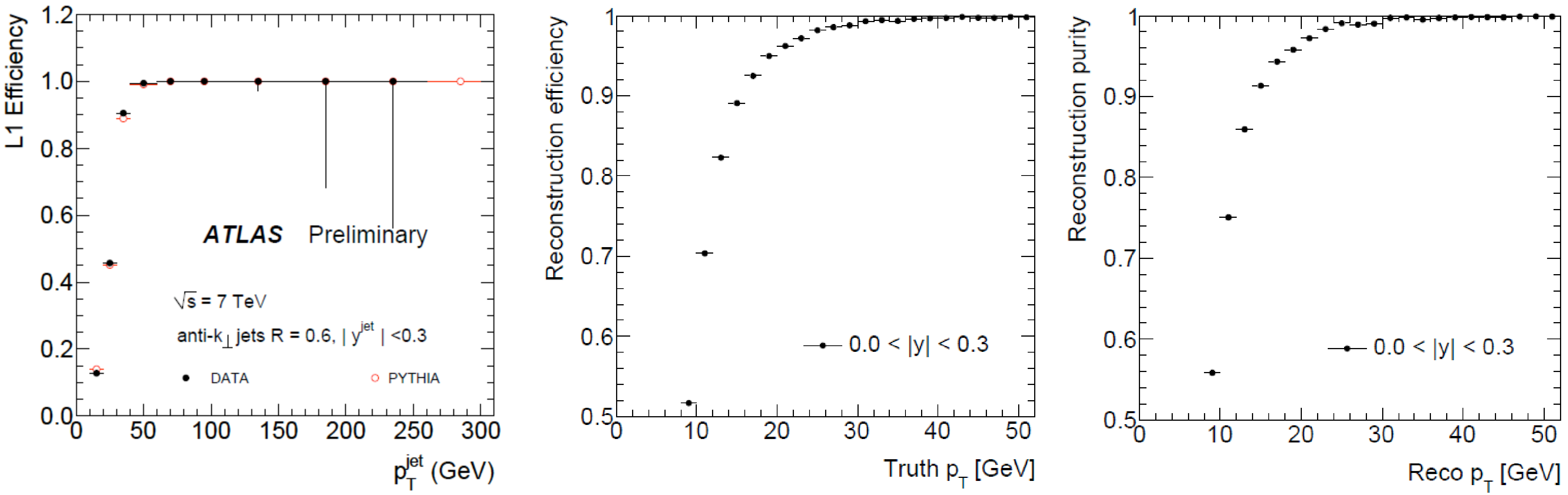
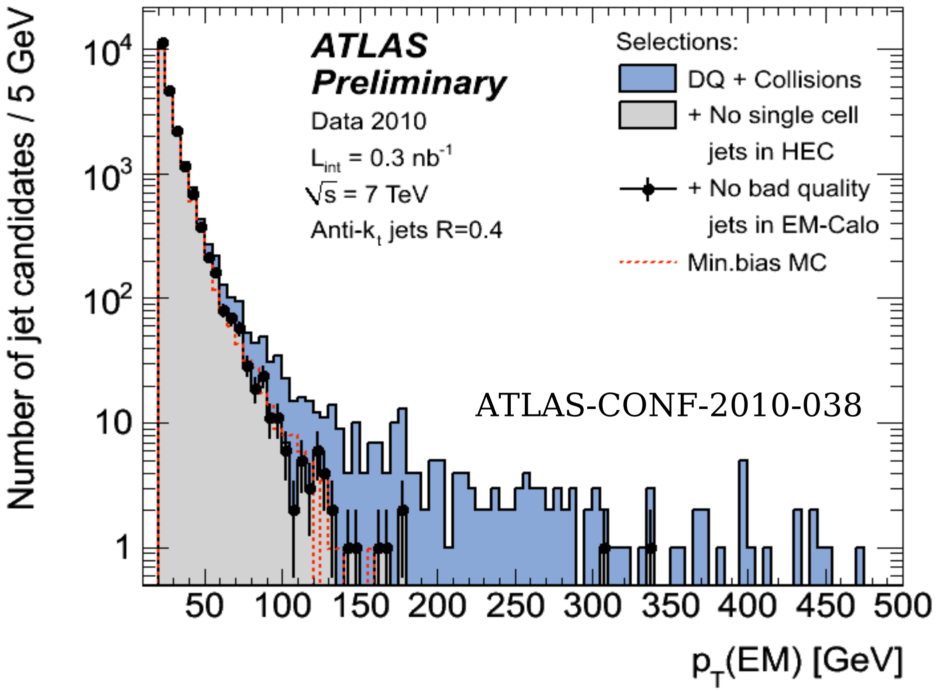


Jet cleaning

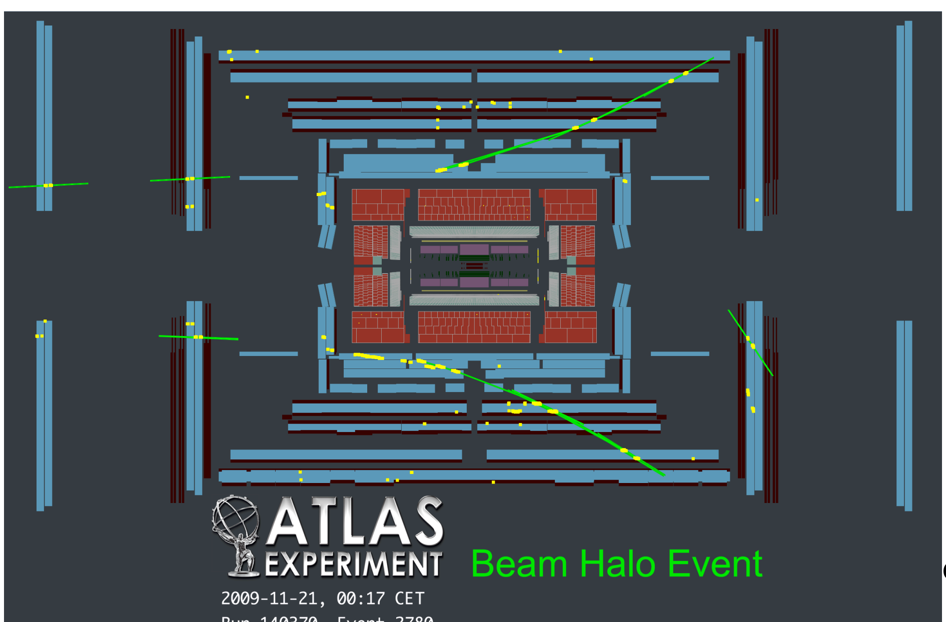
- Events with at least one "bad" jet with p_T >10 GeV at electromagnetic scale anywhere in detector are removed
- "Bad" jet definition is based on cuts designed to remove:

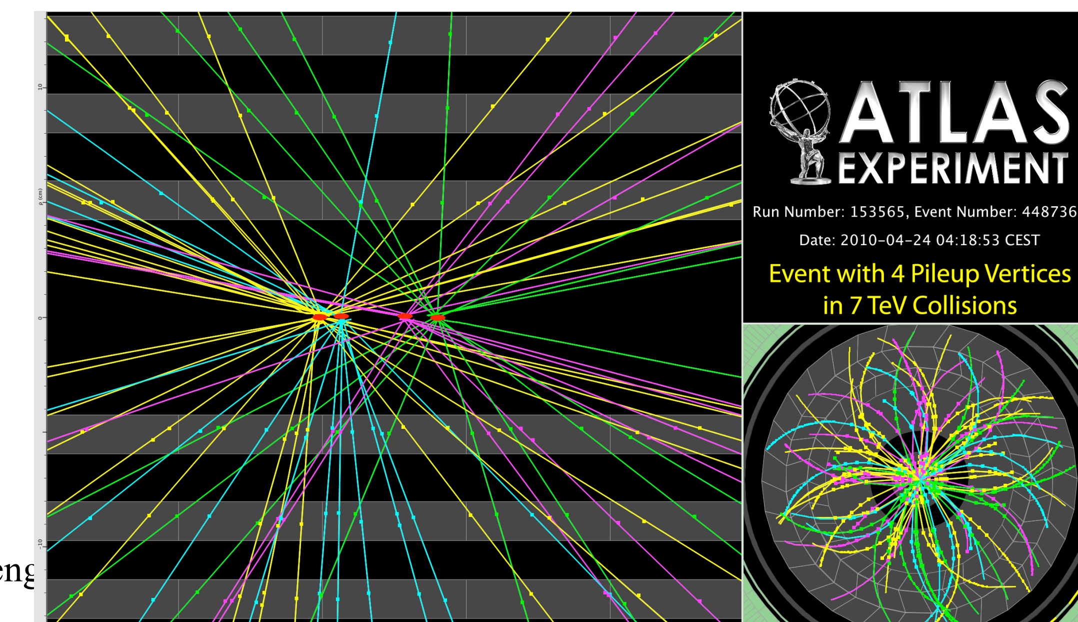


- Noisy cells in the hadronic endcap calorimeter
- Coherent noise in the electromagnetic calorimeter
- Large out-of-time energy depositions, e.g. from cosmic ray muons

Vertex requirement

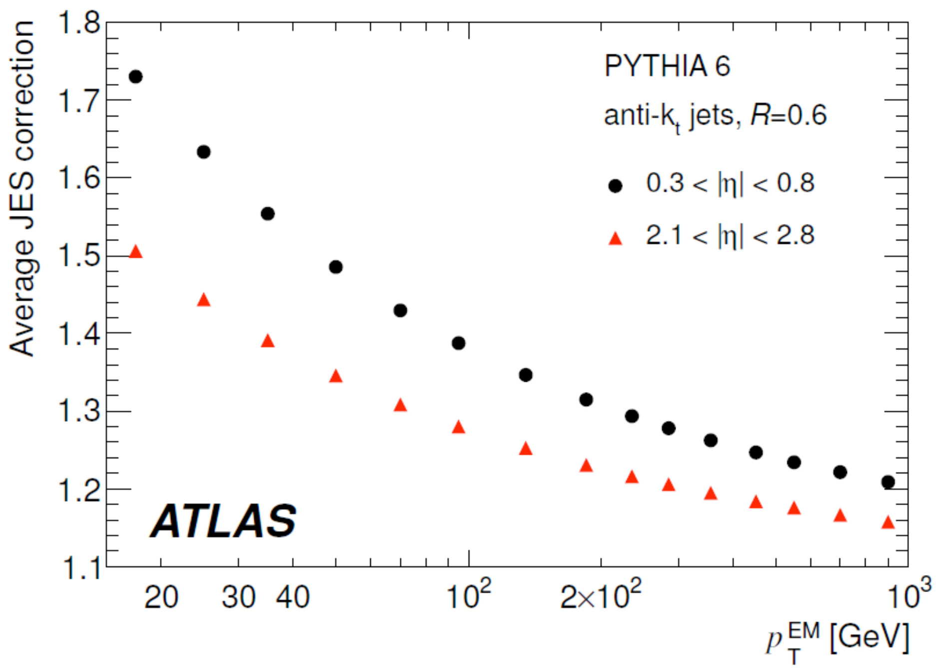
- Require at least one vertex reconstructed with at least 5 tracks and |z|<10cm (luminous region is ~5cm in early data, somewhat wider later)
    - Suppresses contamination from non-collision backgrounds such as beam halo and beam gas
    - 99% efficient for early data
- Effect of pileup is accounted for in absolute JES uncertainty
- |z| vertez cut also helps to ensure that jets are well-measured because they originate from near the detector center

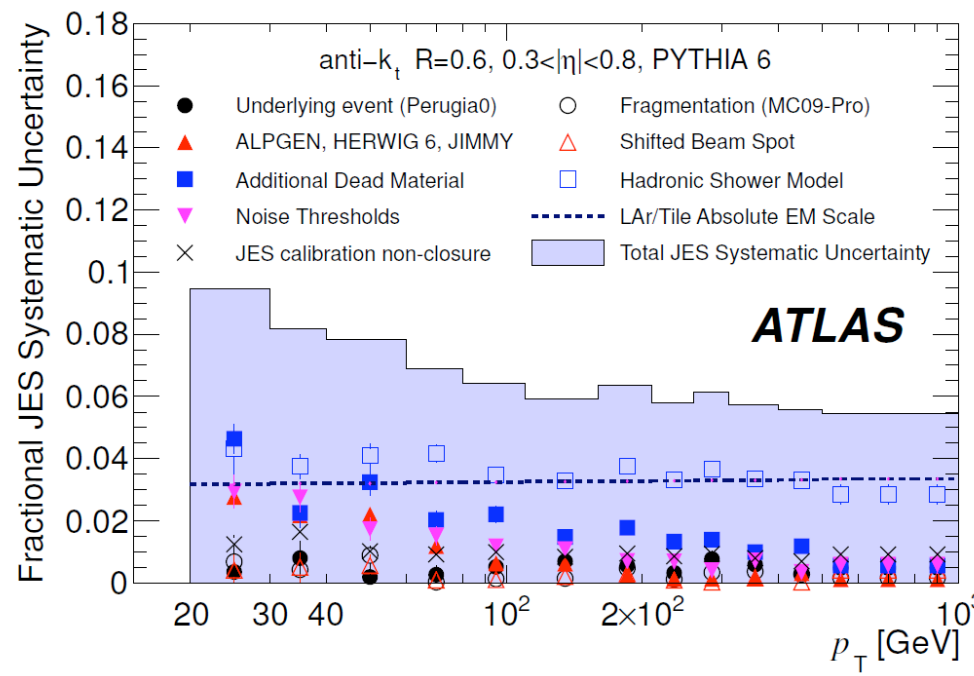




Jet energy scale (JES) calibration

- Jet p_T corrected on average from "EM scale" back to the hadron level using "numerical inversion"
  - MC-based calibration as a function of jet p_T and η
  - Non-linearity for hadrons due to *non-compensation* from nuclear interactions as well as *dead material* upstream
- Absolute JES uncertainty derived via systematic variation of parameters in MC
  - Conservative uncertainty within 7% for central jets with p_T > 60 GeV (dominant systematic uncertainty for most jet measurements)
  - Includes pileup uncertainty estimated using tower energy density





Relative jet energy scale

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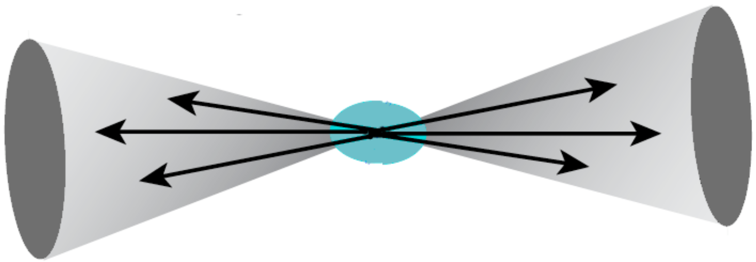
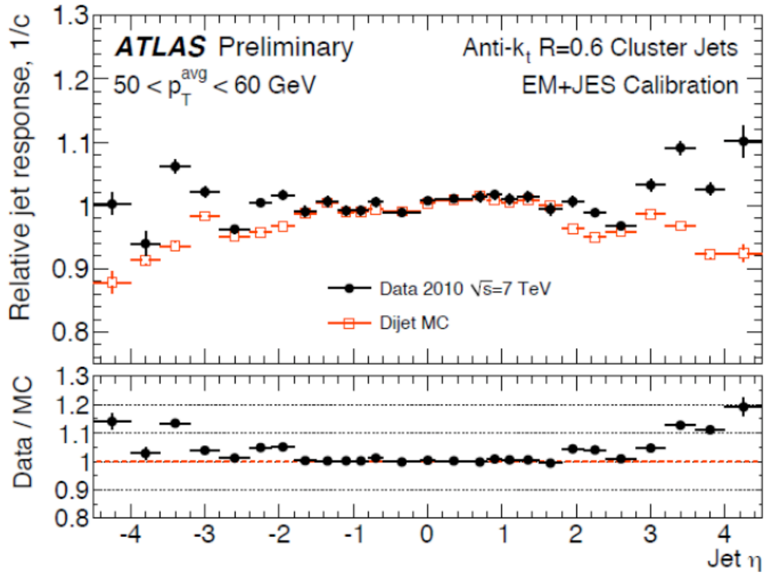
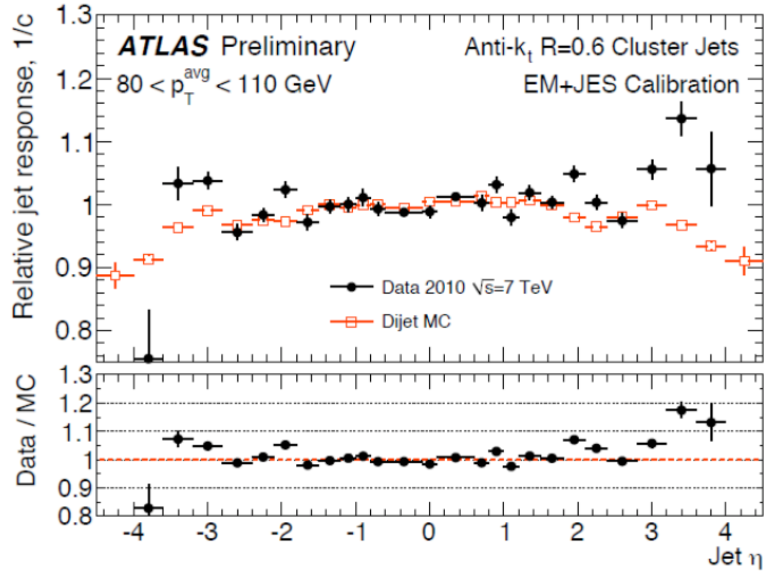
- Absolute JES assumed fully correlated in pseudorapidity
- Unlike single jets, dijets can span a large pseudorapidity → dependence also on the relative JES



- Dijet balance indicates relative JES of 5% within |y|<2.8
- Diverges to 15% in 2.8<|y|<4.5
- Thus restrict to |y|<2.8 when possible





Jet energy resolution

- Jet energy resolution in MC validated to ~14% via dijet balance and bi-sector methods (in-situ)
  - Control for systematic uncertainties from underlying event, initial state radiation, etc
  - Initial studies with more data show agreement within 10%
- Jet angular resolution also verified at the level of 20% at very low p_T using track jets as a proxy

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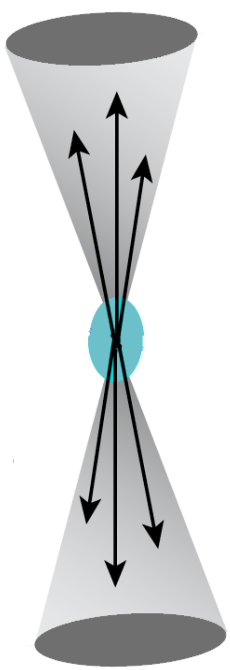
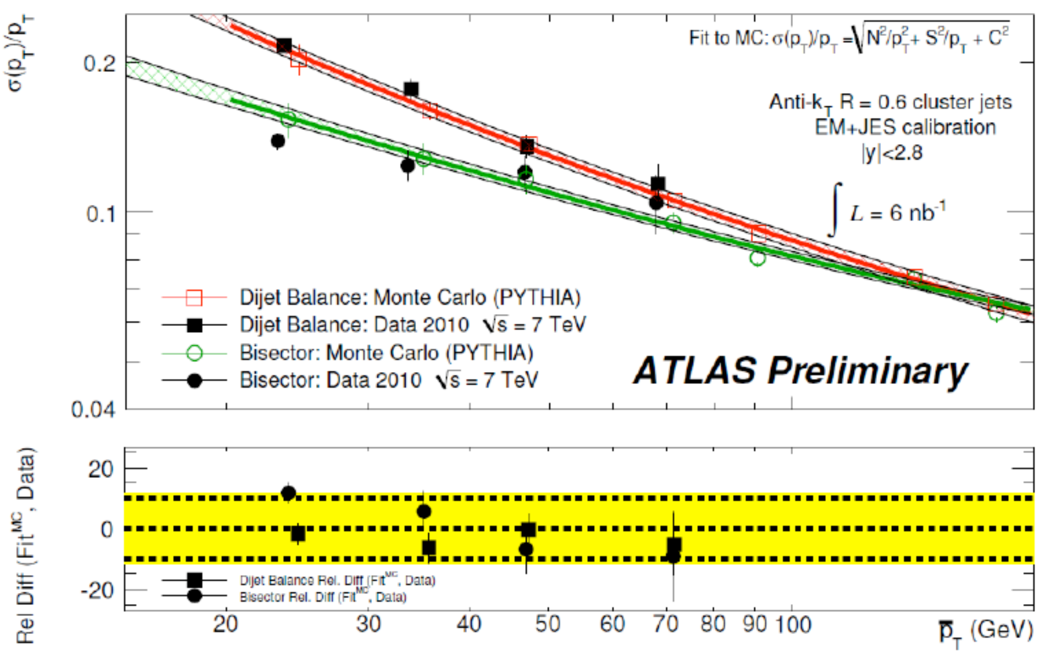


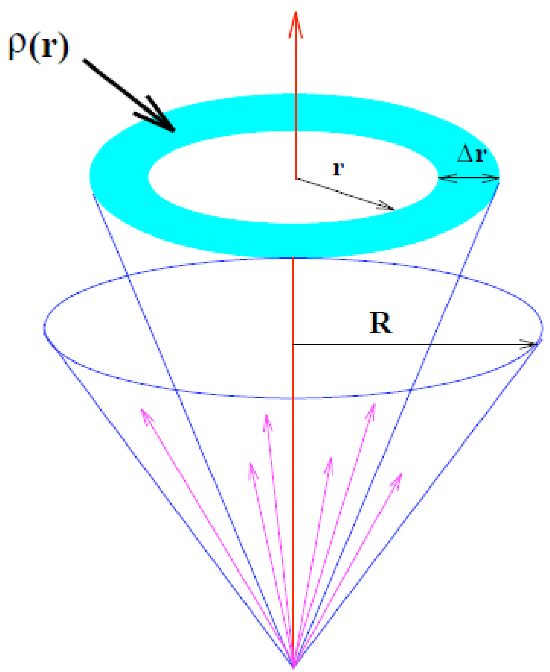


What the internal structure of jets looks like

Differential jet shape: Method

- Differential jet shape in inclusive jet production:

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{jet}}\sum_{\text{jets}}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)},\ 0 \le r \le R$$



is the average *fraction* of jet transverse momentum within annulus of inner radius (r – Δr/2) and outer radius (r + Δr/2)

- Proportional to transverse momentum density inside the jet
- Relatively insensitive to the jet energy scale because jet p_T normalized away

- Here p_T is computed as the scalar sum of transverse momenta of calorimeter energy clusters that lie within the annulus

Differential jet shapes: Results

- Jet shapes from calorimeter clusters used as basic validation
- Density of transverse momentum peaks at low r with most of jet p_T within r<0.3, indicating collimated flows of particles around jet axis
- Shifts to lower r for higher p_T jets, indicating they are more collimated

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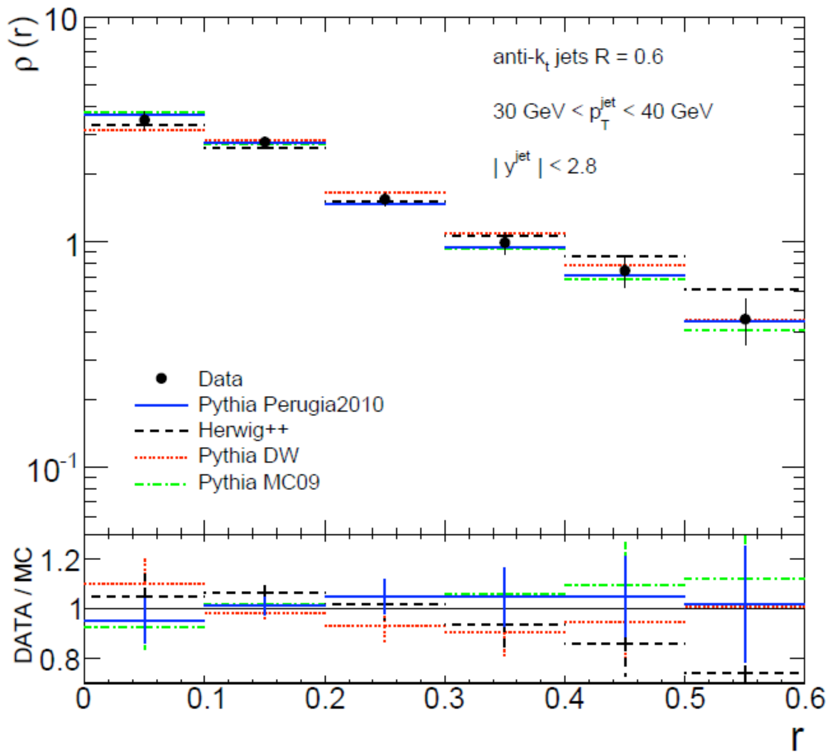

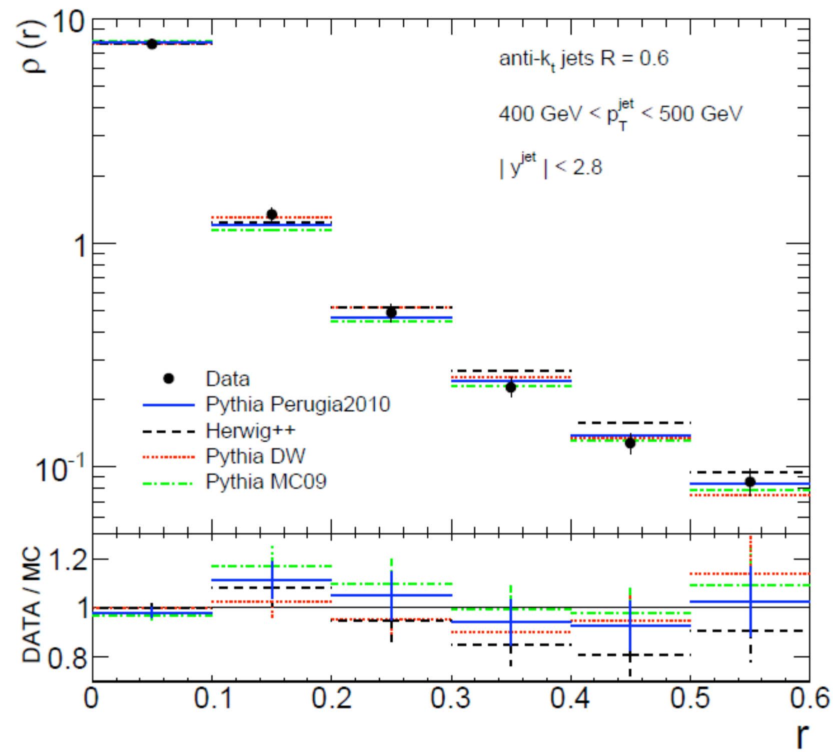

How often are jets produced, and does this agree with NLO pQCD?

Unfolding

- Bin-by-bin unfolding back to hadron level, where all particles with lifetime > 10 ps (including muons and neutrinos) are included
- Correct for all detector effects: efficiencies, scales, and resolutions
  - Jet trigger efficiency
  - Vertex reconstruction efficiency
  - Jet reconstruction efficiency
  - Absolute and relative jet energy scale
  - Jet energy resolution
  - Jet angular resolution
- Strategy: Restrict kinematic region and bin the observable sufficiently coarsely so that corrections are both small and stable
- Do not correct for acceptance from p_T and rapidity cuts
  - These are part of definition of the observable and no measurement is made outside this range

Unfolding systematics

- Use Pythia MC09 to derive correction factors:

$C = \sigma_{truth} / \sigma_{reco}$

- Systematic uncertainty on this correction factor studied by:
    - Scaling up/down by JES uncertainty (dominant effect, not shown)
    - Worsening jet energy resolution by 15%
    - Smear angular resolution by 5%
    - Reweight cross-section to alter shape of distribution

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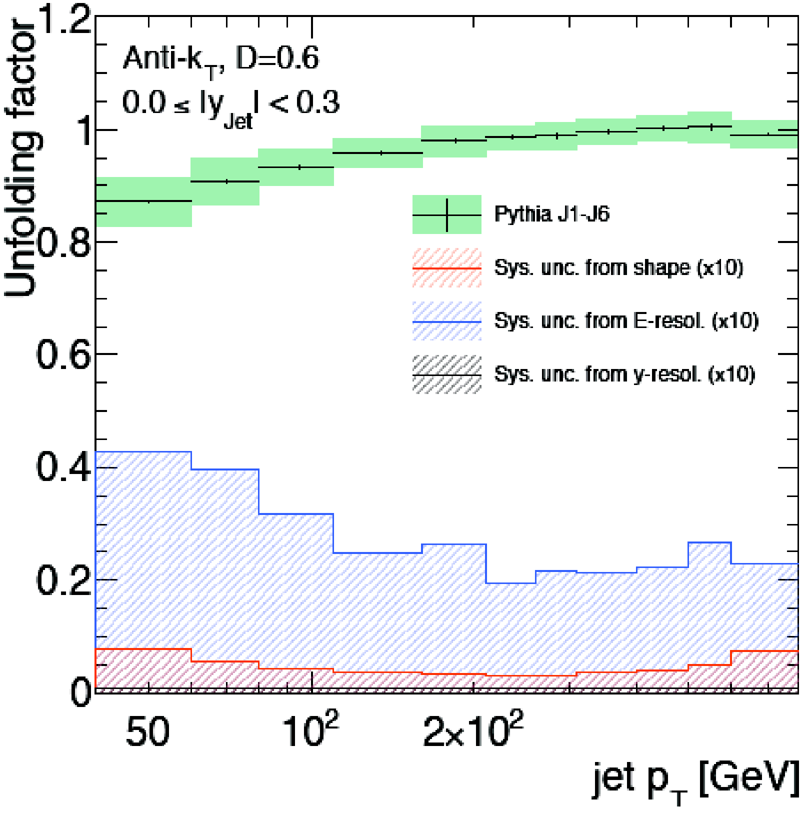

- Also perform closure tests against Pythia 8, Herwig++, and Alpgen

Theory prediction & uncertainties

- Monte Carlo used for observables with high jet multiplicity
  - LO 2->2: Pythia, Herwig
  - LO 2->N: Alpgen (matrix element generator)
- NLOJet++ used to calculate NLO pQCD prediction for low jet multiplicity
  - APPLgrid program used for efficient evaluation of uncertainties
  - **CTEQ 6.6 NLO PDF** is baseline, but also compared to MSTW 2008 NLO, NNPDF 2.0 NLO, HERA 1.0 NLO

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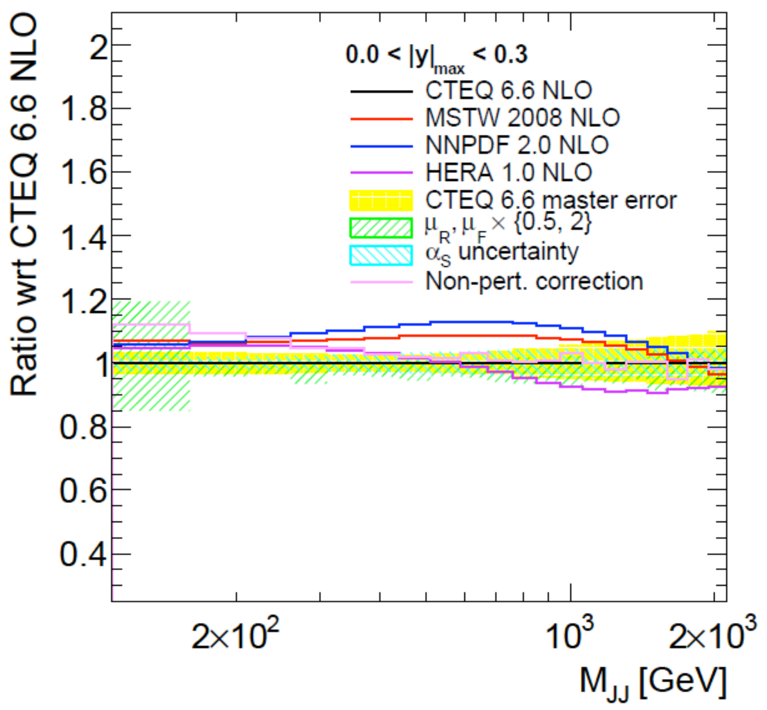
- Renormalization scale μ_R varied by factor of 2 to account for neglected higher order terms
- Factorization scale μ_F varied by factor of 2 to account for scale separating matrix element from PDF evolution
- Strong coupling constant $\alpha_s(M_Z)=0.118$ varied by 0.002 from world's best estimate



Non-perturbative correction

- **Parton-level NLO calculation** corrected for non-perturbative effects calculated using Rivet framework:
  - *Hadronization* and *underlying event*
  - Different dependence for R=0.4 (left) and 0.6 (right) $\rightarrow$ tune MC!
- Systematic variations assessed using:
  - Perugia0, Perugia hard, Perugia soft, Herwig

Dominated by UE

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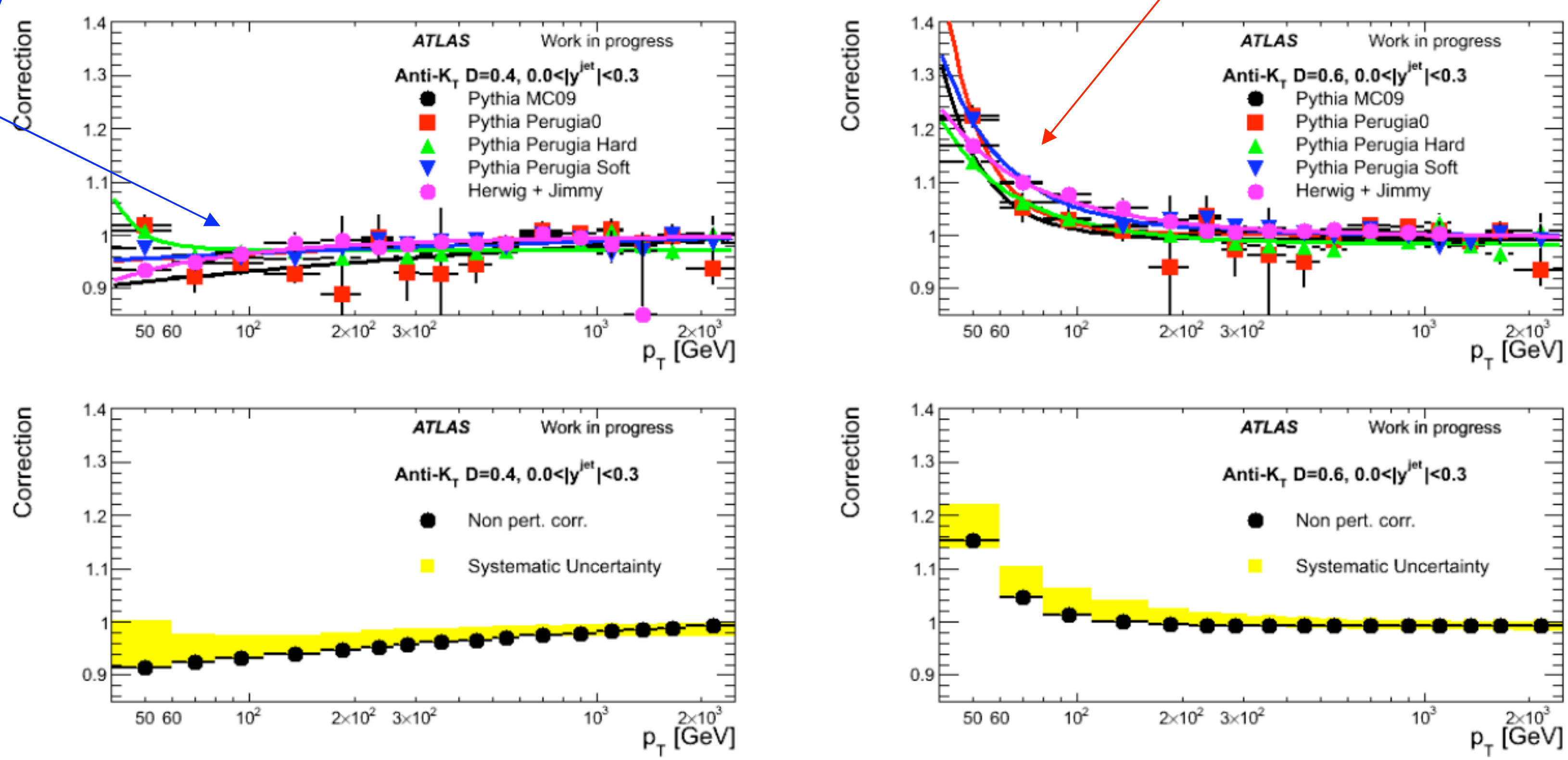
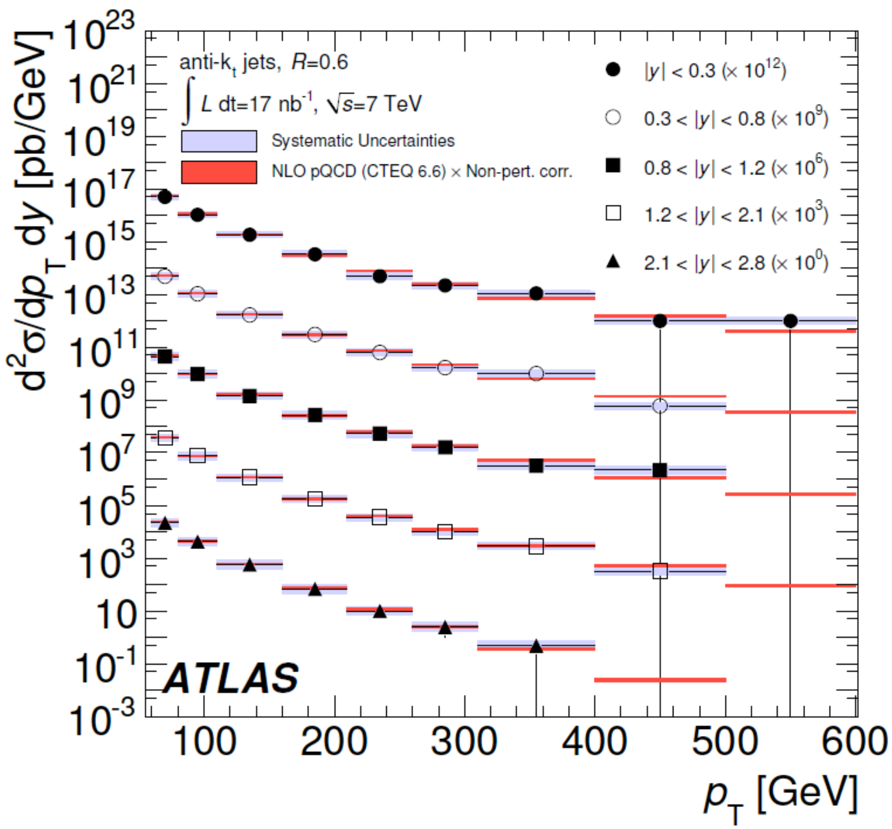
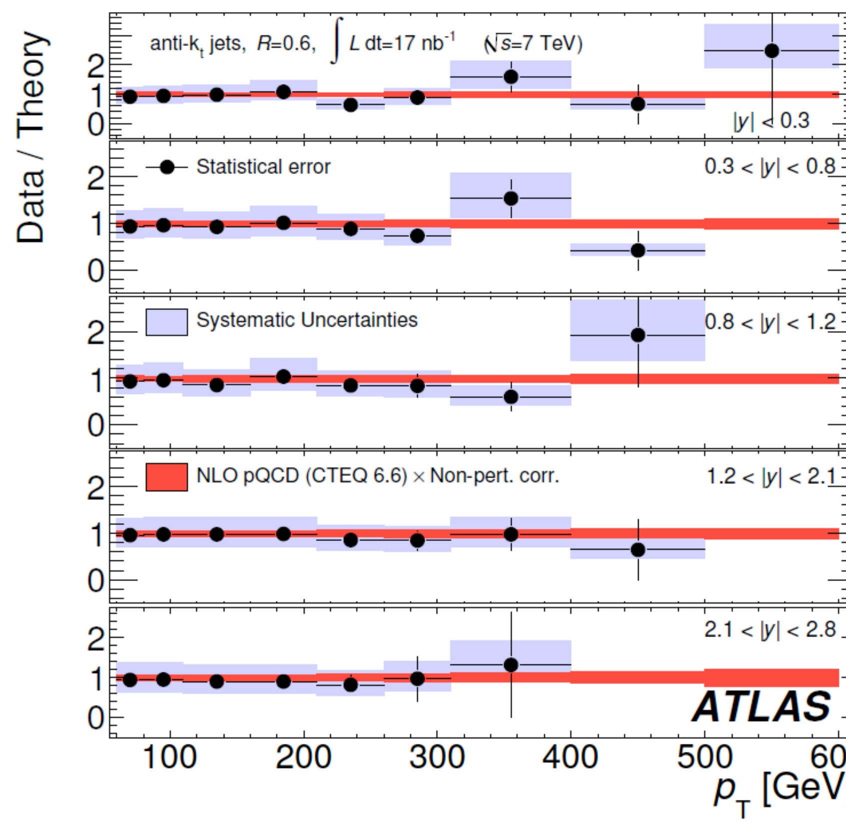
Dominated by hadronization



Inclusive jet p_T cross-section

- ATLAS Collaboration. "Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy with the ATLAS detector." arXiv:1009.5908 [hep-ex]. Accepted by Eur. Phys. J. C.
- First cross-section measurements at a center-of-mass energy of 7 TeV of inclusive jet and dijet production, using 17 nb^{-1} integrated luminosity
- Inclusive jet cross-section = Probability to observe a jet in a *pp* collision as a function of the jet p_T and rapidity (canonical single-jet observable)

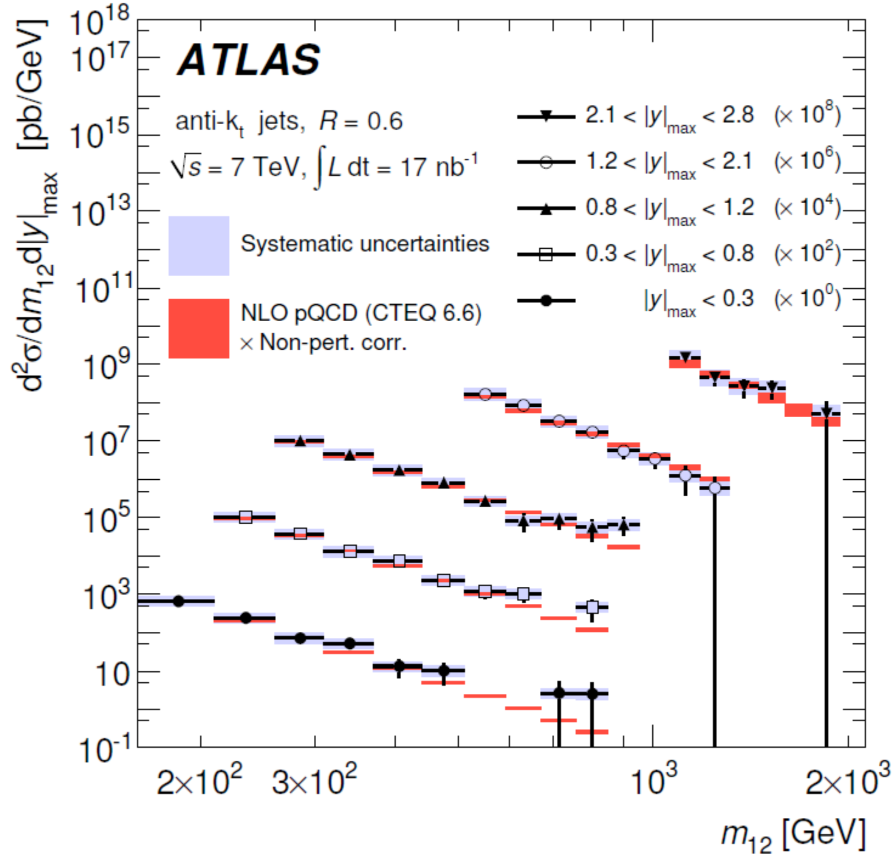




Dijet mass spectrum

Dijet mass = invariant mass of two leading jets measured in bins of maximum rapidity of two leading jets: $|y_{max}| = \max(|y_1|, |y_2|)$

- Exotic resonances would tend to decay to high p_T central jets
- QCD produces more low p_T forward jets separated by large opening angle
- No discrepancy observed between data and NLO pQCD prediction

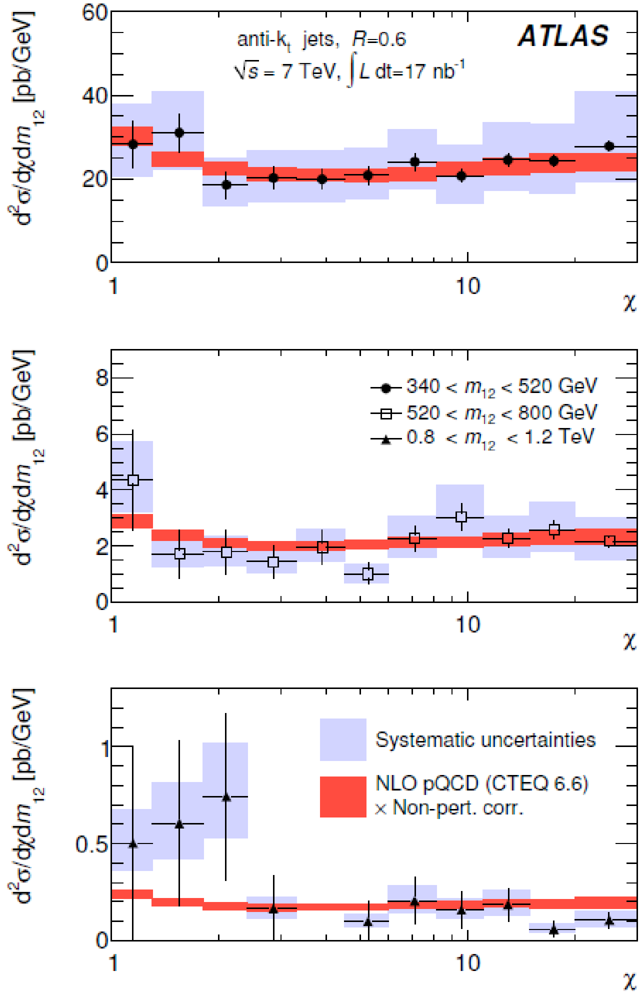


Dijet χ angular distribution

Dijet angular distribution: $\chi = \exp(\,|y_1 - y_2|\,) = (\,1+\cos(\theta^*)\,) / (\,1-\cos(\theta^*)\,)$

measured in bins of dijet mass $m_{1\,2}$

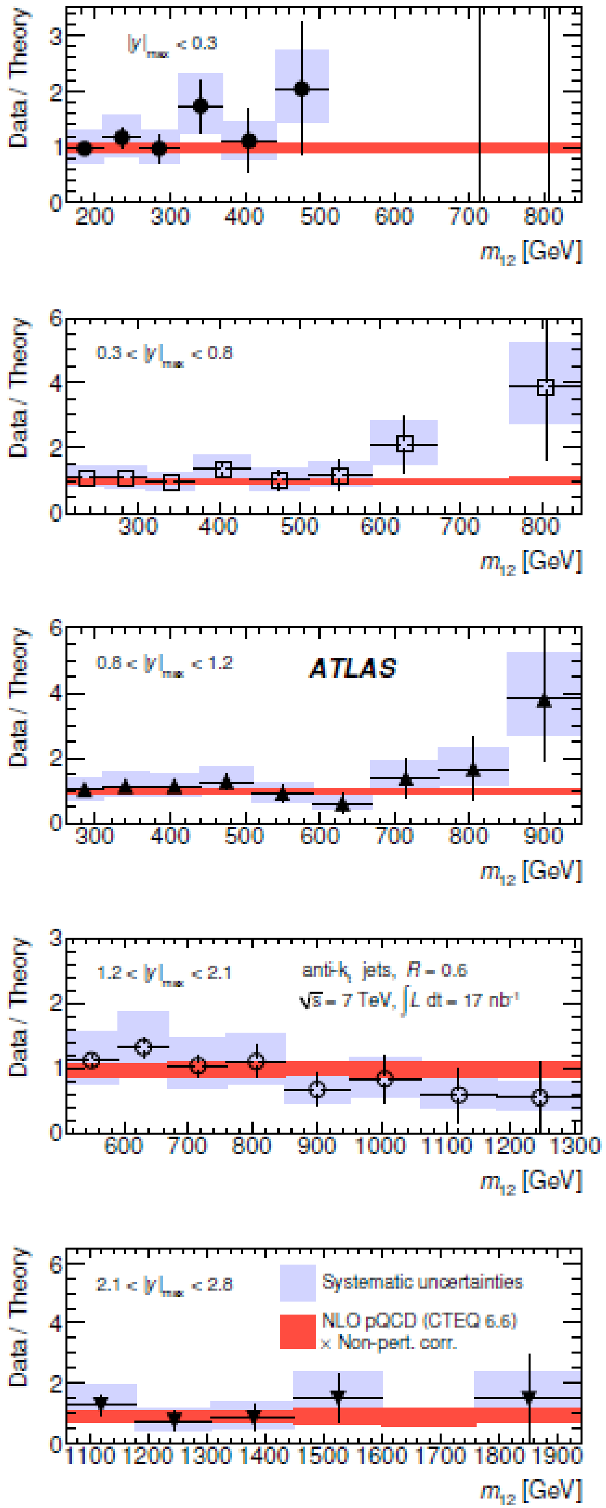
- Measures scattering angle θ^* in dijet center-of-mass frame
- Contact interactions such as compositeness would produce peak at low χ (small scattering angle), whereas QCD is ~ flat as we see
- Relatively insensitive to parton distribution functions because predictions for gg, qg, and qq subprocesses are similar
- No statistically significant deviations seen wrt pQCD prediction

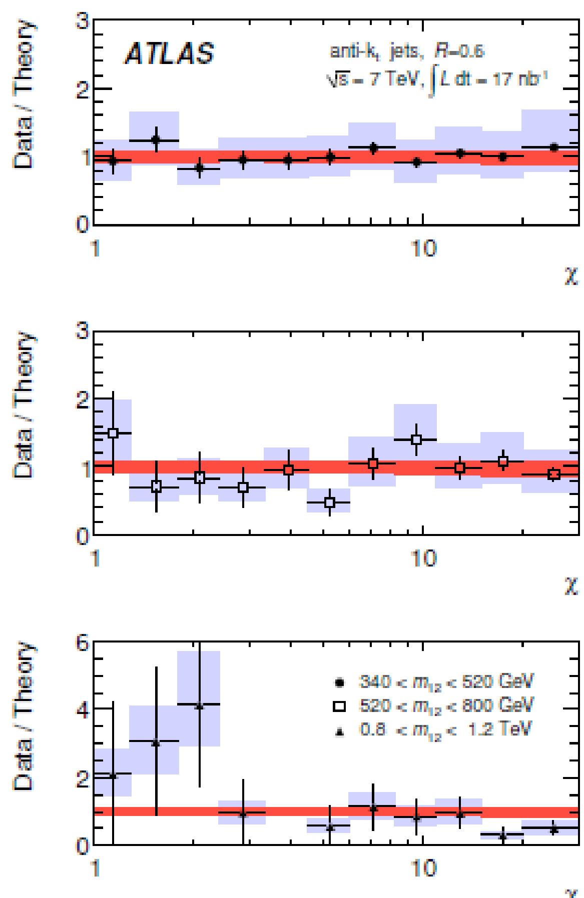


Dijet mass and χ: Data/theory ratio

NLO pQCD describes data well in all regions of phase space

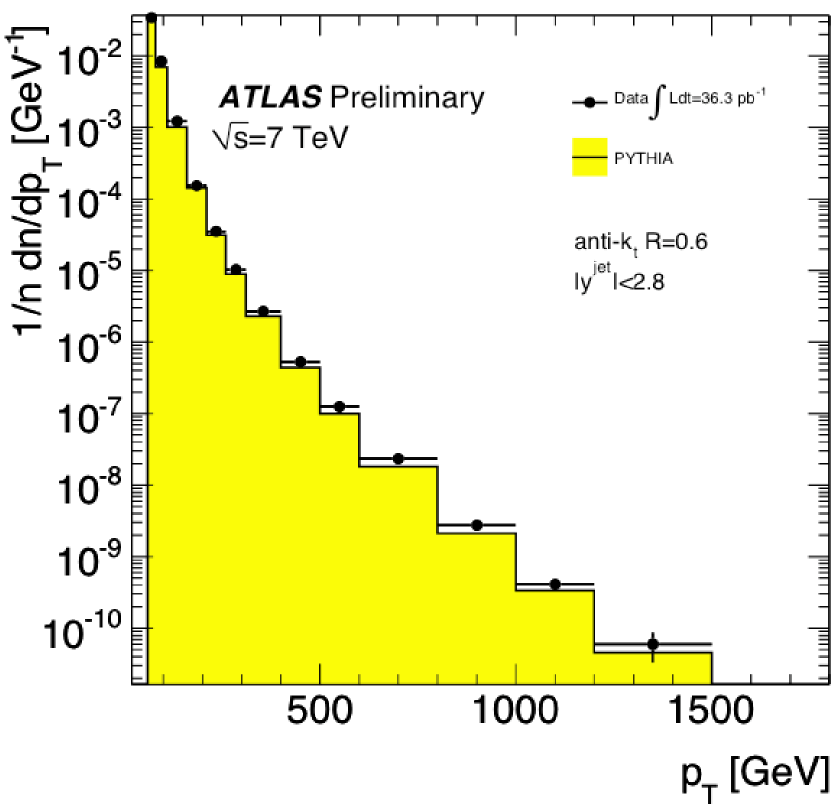
- Both central and forward dijet mass follow the data (left)
- Angular distribution is as expected from pQCD at large dijet mass (right)

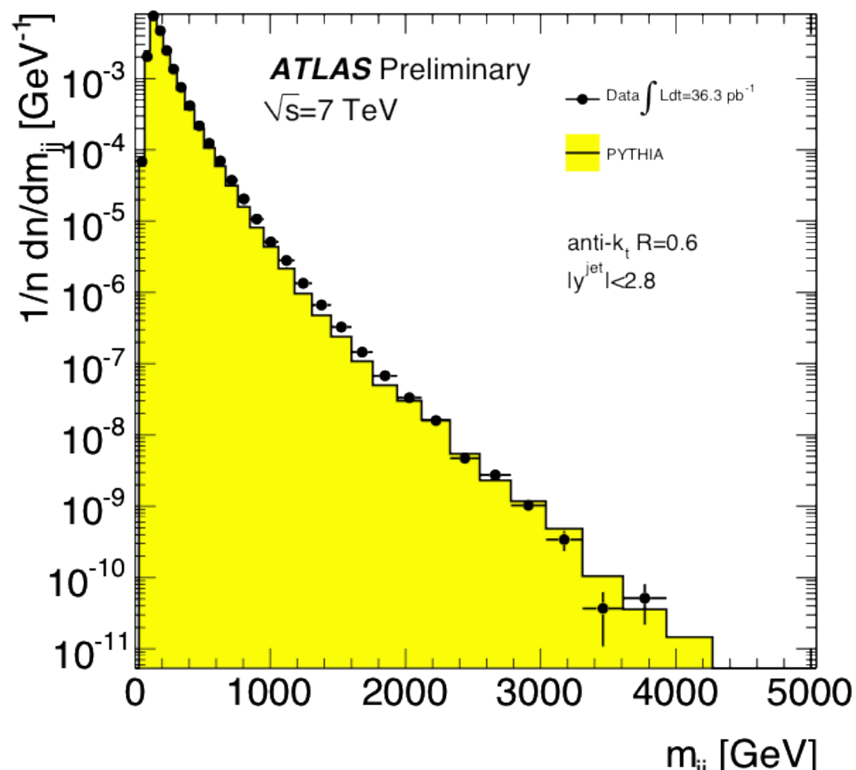




Updated analysis with full 2010 dataset

- Full cross-section measurement with ~45 pb^{-1} integrated lumi taken in 2010 is in progress
- Jets with transverse momentum up to 1.3 TeV are observed
- Invariant mass of two leading jets is observed up to 3.7 TeV
  - LO parton shower Monte Carlo provided to guide the eye
- For Winter 2011 conferences, also extending analysis down to jet p_T of 20 GeV and higher in rapidity to $|y|<4.4$



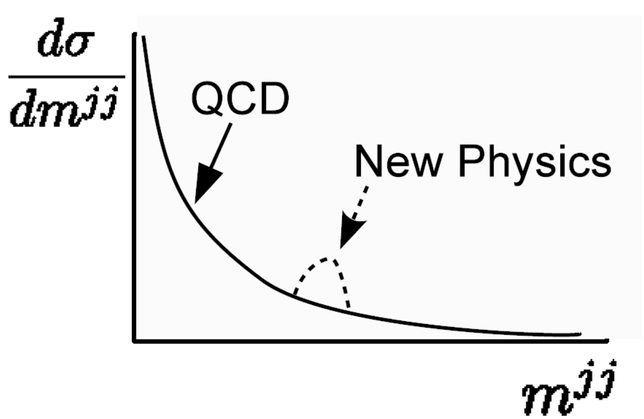


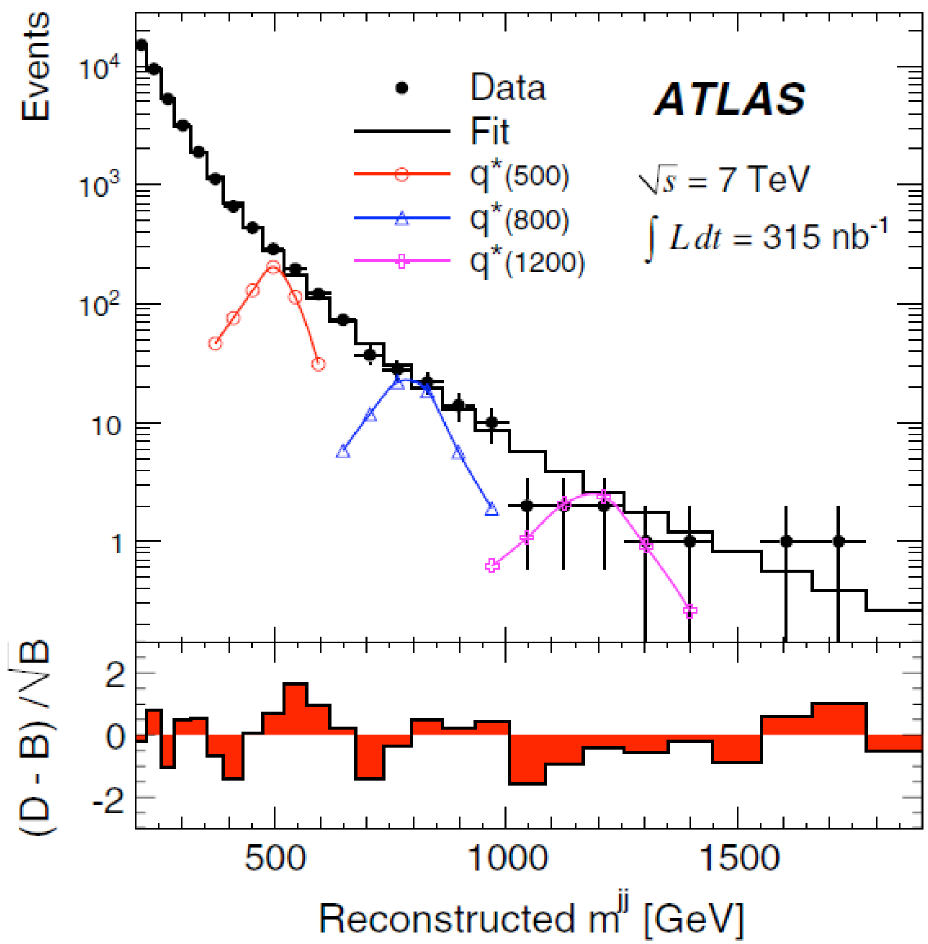
Are there any signs of new exotic physics at these short length scales?

Search for dijet resonance using the dijet mass spectrum

- There are direct extensions to searches for resonances decaying to two jets in final state (excited quarks, technirho, KK graviton, W'/Z', etc)
- Performed a search for bumps in the dijet mass spectrum by comparing it against a smooth continuum as predicted by QCD:

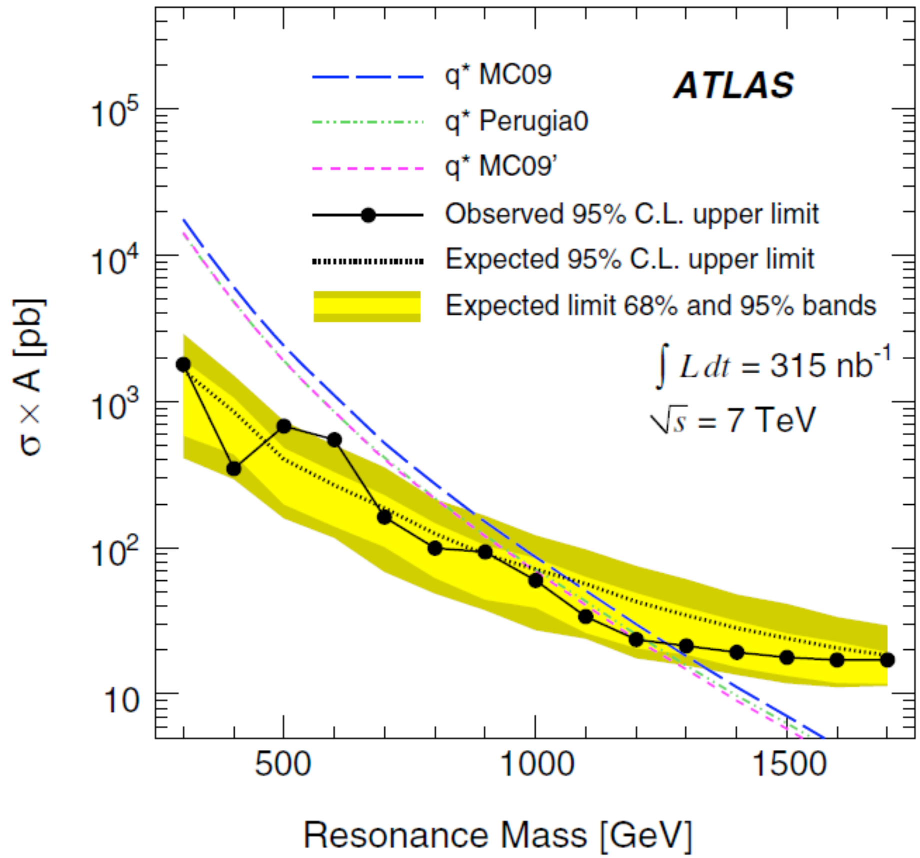
$$f(x) = p_0 \frac{(1-x)^{p_1}}{x^{p_2+p_3 \ln x}}, \quad x \equiv \frac{m^{jj}}{\sqrt{s}}$$





Limit on excited quarks

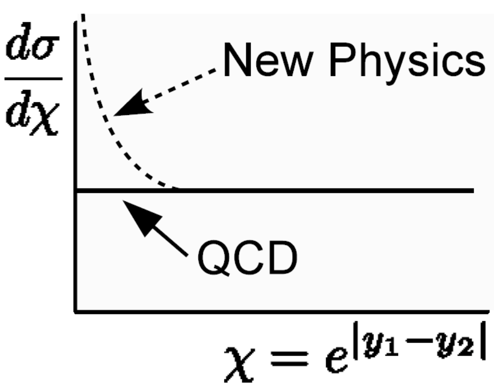
- No evidence of a resonance observed → set new limit on dijet resonances arising from excited quarks
  - Bayesian approach used to set limit, cross-checked with frequentist method
- Excited quarks with mass up to 1.26 TeV excluded at 95% CL
  - Tevatron limit = 870 GeV
  - Systematics including JES (dominant), luminosity, background fit, etc also accounted for

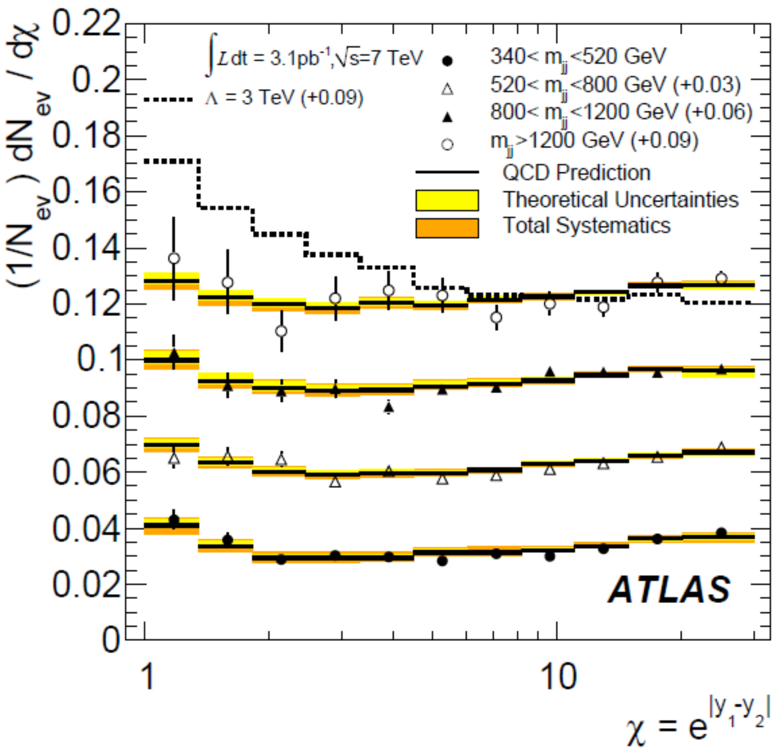


- ATLAS Collaboration. "Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC." Phys Rev. Lett. 105, 161801 (2010)

Search for contact interactions with the dijet χ angular distribution

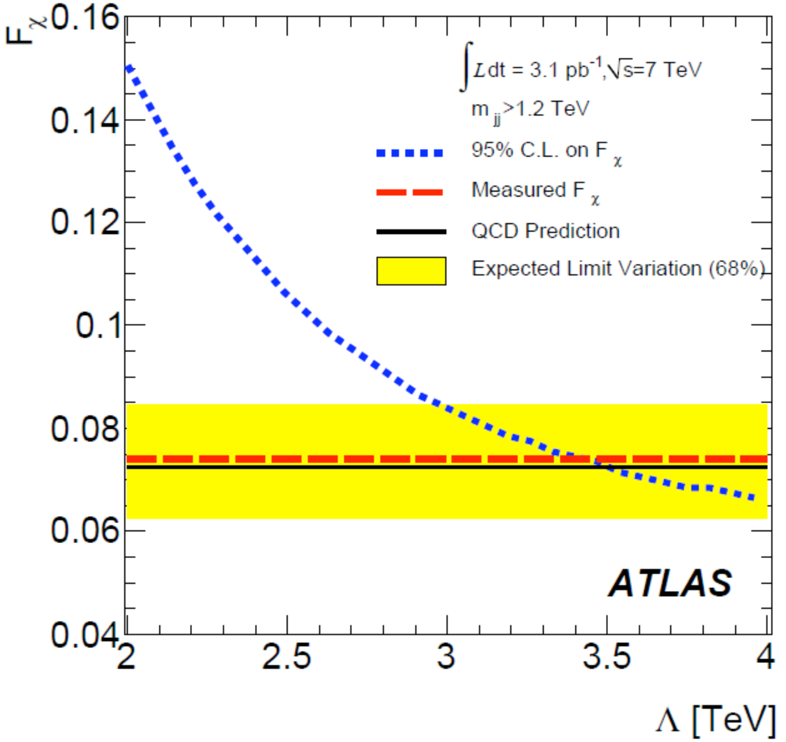
- Examined dijet $\chi = \exp(|y_1 - y_2|)$ angular distribution for excess of low-angle scattering compared to NLO QCD prediction:
  - Normalized distribution mostly cancels out absolute JES uncertainty, leaving relative JES
- Any tail could be indication of contact interaction that might arise from quark compositeness, gravitational scattering, etc.





Limits on contact interactions

- No significant excess observed
- Set new limit on contact interactions that may arise from quark compositeness
  - Define F as fraction of events at low χ
  - Limit set using frequentistic method, cross-checked by Bayesian approach
- Using integrated luminosity of 3.1 pb^{-1}, compositeness scale Λ < 3.4 TeV excluded at 95% CL
  - Tevatron limit = 3.1 TeV



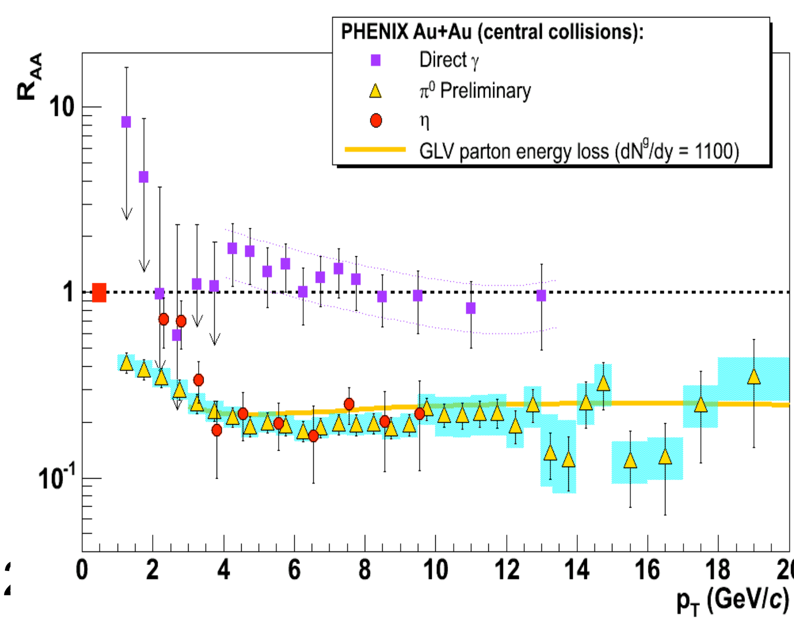
- ATLAS Collaboration. "Search for Quark Contact Interactions in Dijet Angular Distributions in pp Collisions at sqrt(s) = 7 TeV Measured with the ATLAS Detector." arXiv:1009.5069 [hep-ex]. Accepted by Phys. Lett. B.

Surprises from jets in lead ion collisions

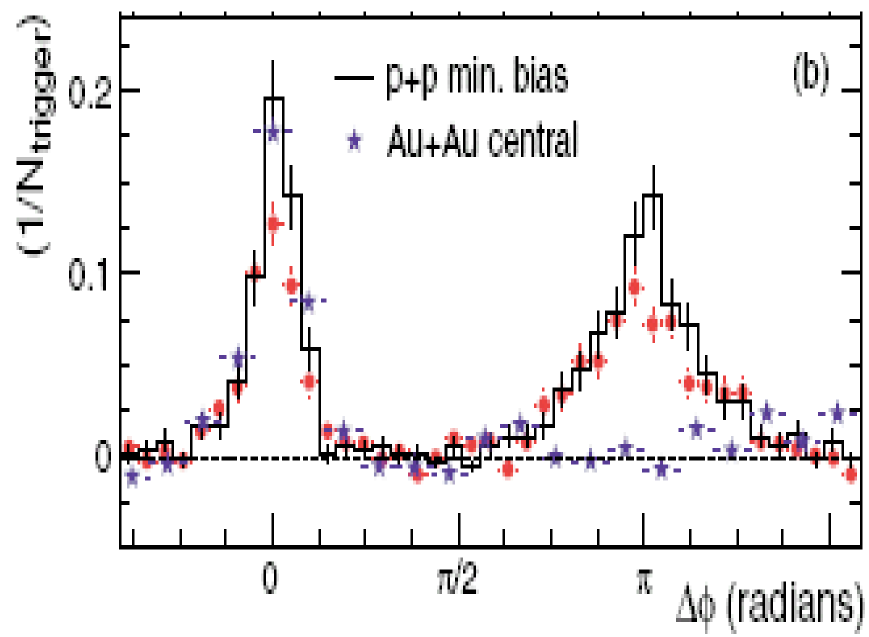
Jet quenching at RHIC

- Jet quenching was first observed in gold ion collisions at sqrt(s_{NN}) = 100 GeV at the Relativistic Heavy Ion Collider
  - Single hadron suppression, no photon suppression (PHENIX)
  - Dijet “disappearance” in di-hadron correlations (STAR)
    - LBL theorists & experimentalists in nuclear physics played key roles in theory, hardware, and analysis

PHENIX

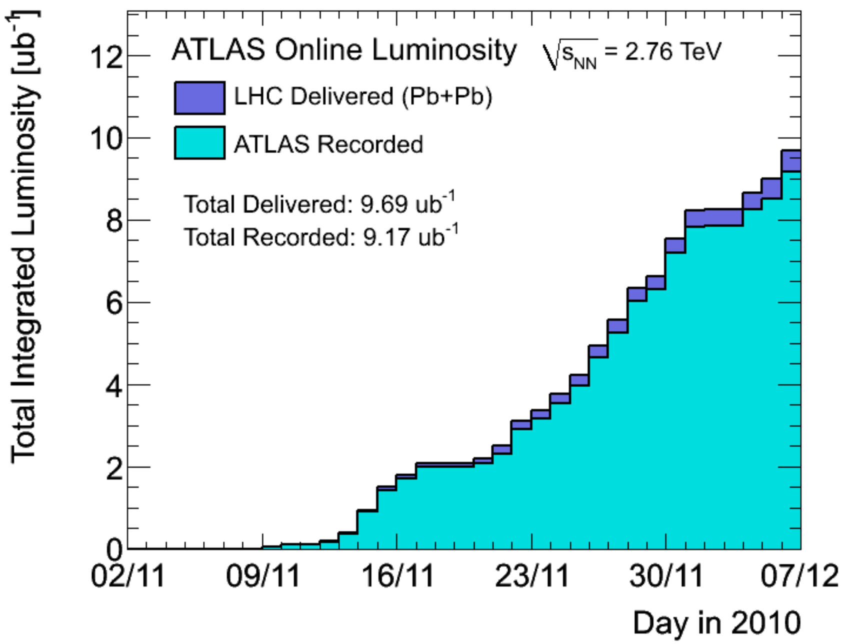


STAR



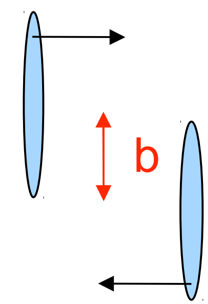
Lead ion collisions at the LHC

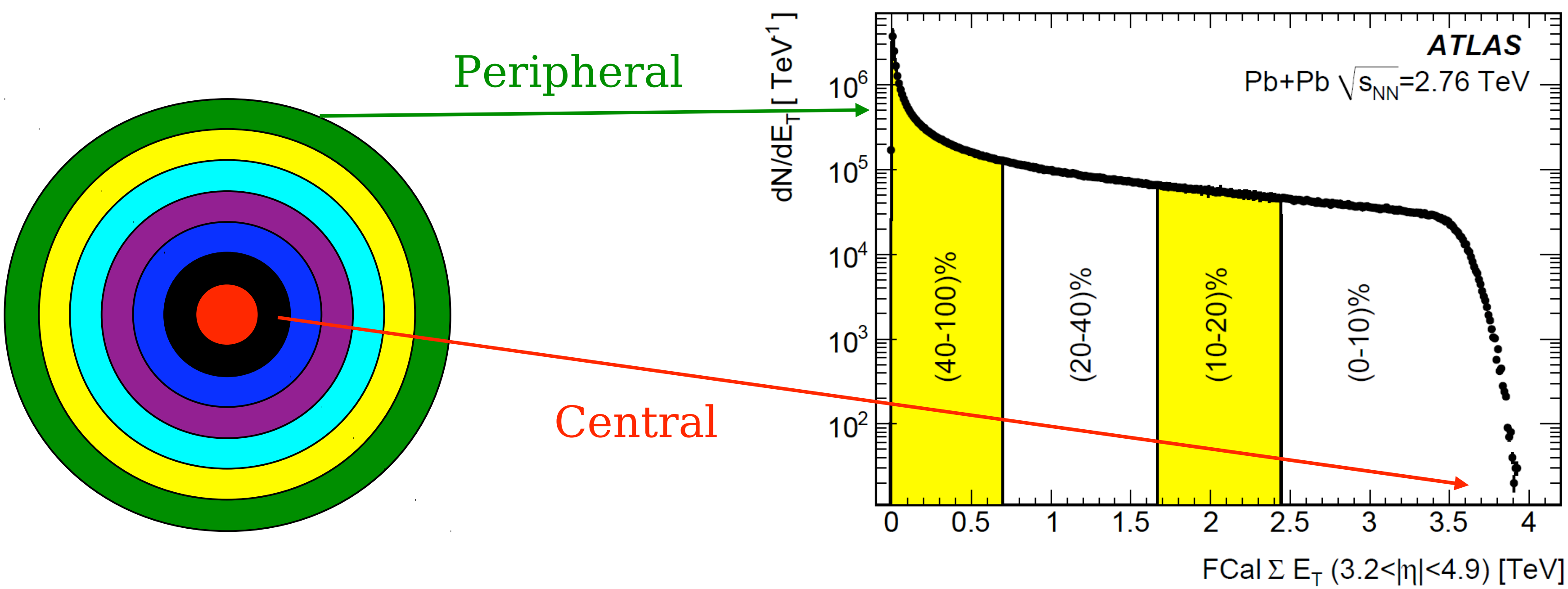
- LHC collided lead ions at sqrt(s_{NN}) = 2.76 TeV in November
- Approximately 9 ub^{-1} recorded
  - Results shown here use 1.7 ub^{-1}, with analysis of rest of data on-going



Centrality definition

- Particle multiplicity increases as classical impact parameter b decreases
- Characterize centrality by percentiles of total cross-section using $\Sigma\, E_T$ in Forward Calorimeter (FCal) spanning $3.2 < |\eta| < 4.9$
    - Recover pp behavior in peripheral collisions where nuclear "overlap" is small





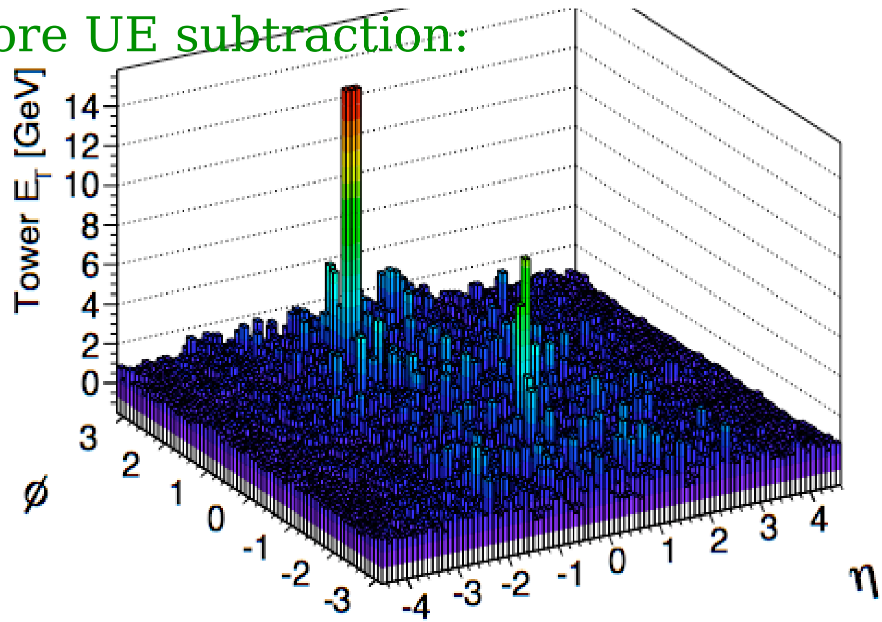
Event selection

- Events triggered using minimum bias trigger
- Jets reconstructed from calorimeter towers using anti-k_T algorithm with R=0.4
  - Calibrated with energy density cell weighting
  - UE subtraction performed afterwards (next slide)
- Two leading jets are required to be within $|\eta_{1,2}| < 2.8$ where relative JES uncertainty is within 5% from pp data
- Jet $E_{T,1} > 100$ GeV so jet reconstruction in lead ion collisions is fully efficient
- Jet $E_{T,2} > 25$ GeV to be above UE background
  - Opposite hemisphere ($\Delta\varphi > \pi/2$) to select fairly “back-to-back” dijet events

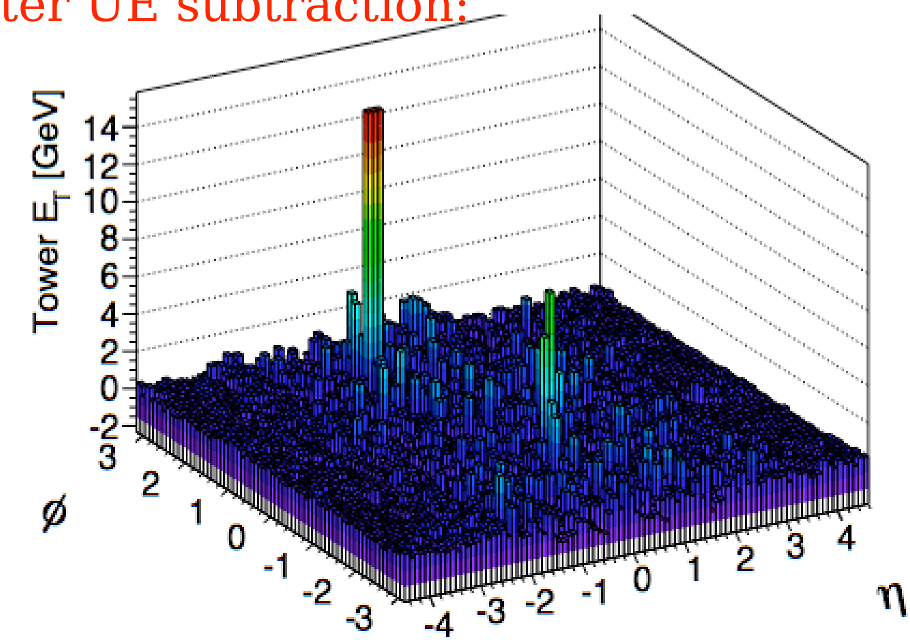
UE subtraction from jet

- Underlying event in heavy ion collisions is huge → critical to correct jet E_T
- UE density is computed for each longitudinal layer, in slices of $\Delta\eta = 0.1$
  - Average over φ (elliptical flow)
  - Exclude towers from calculation of UE density if discriminant $D = E_t^{tower, max} / E_t^{tower, mean} > 5$ (no jets are removed from analysis)
- Jet correction is the UE density integrated against jet area
  - R=0.2 and R=0.4 used for cross-checks because UE pedestal for each jet scales with area i.e. R^2 → results are consistent

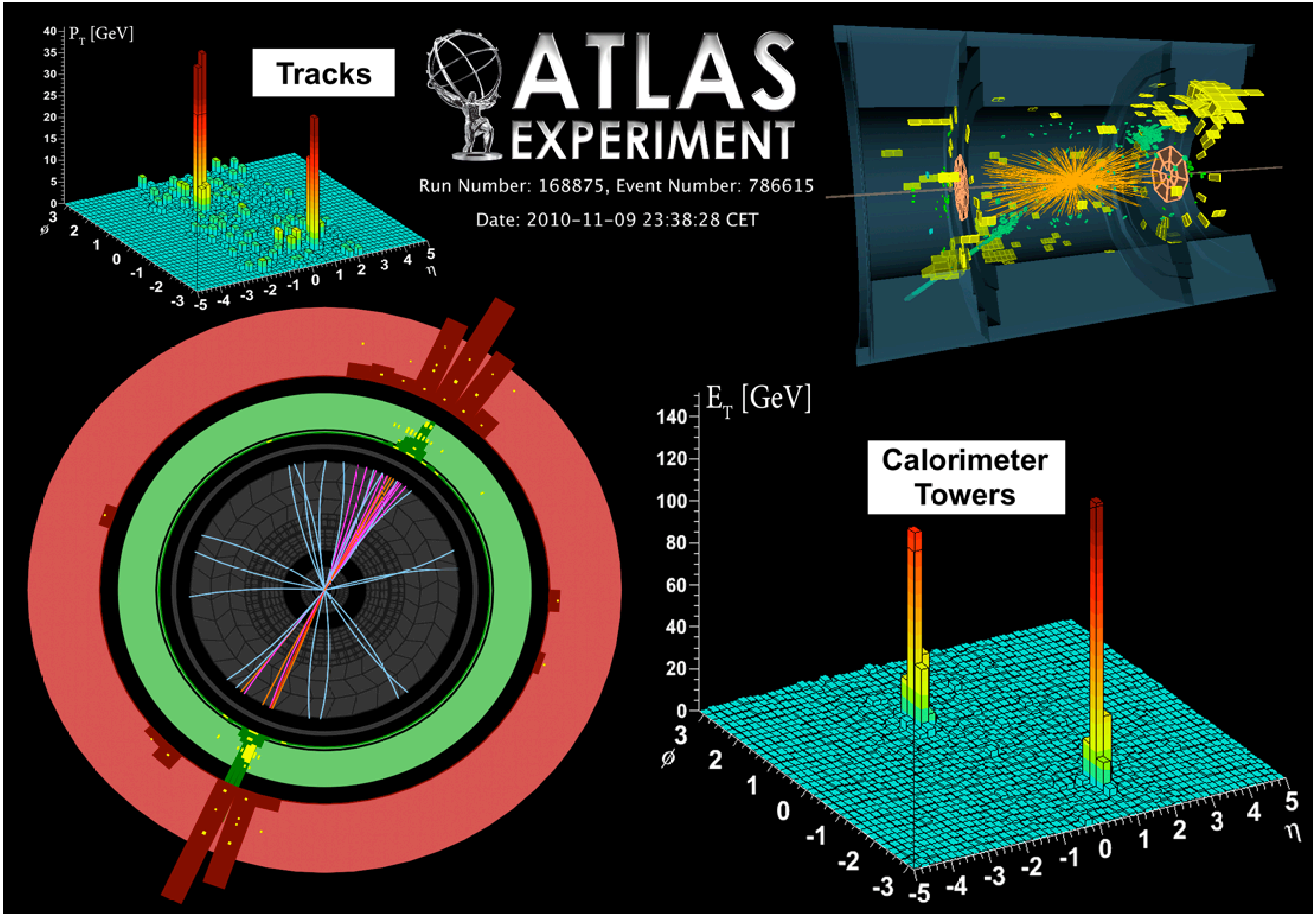
Before UE subtraction:



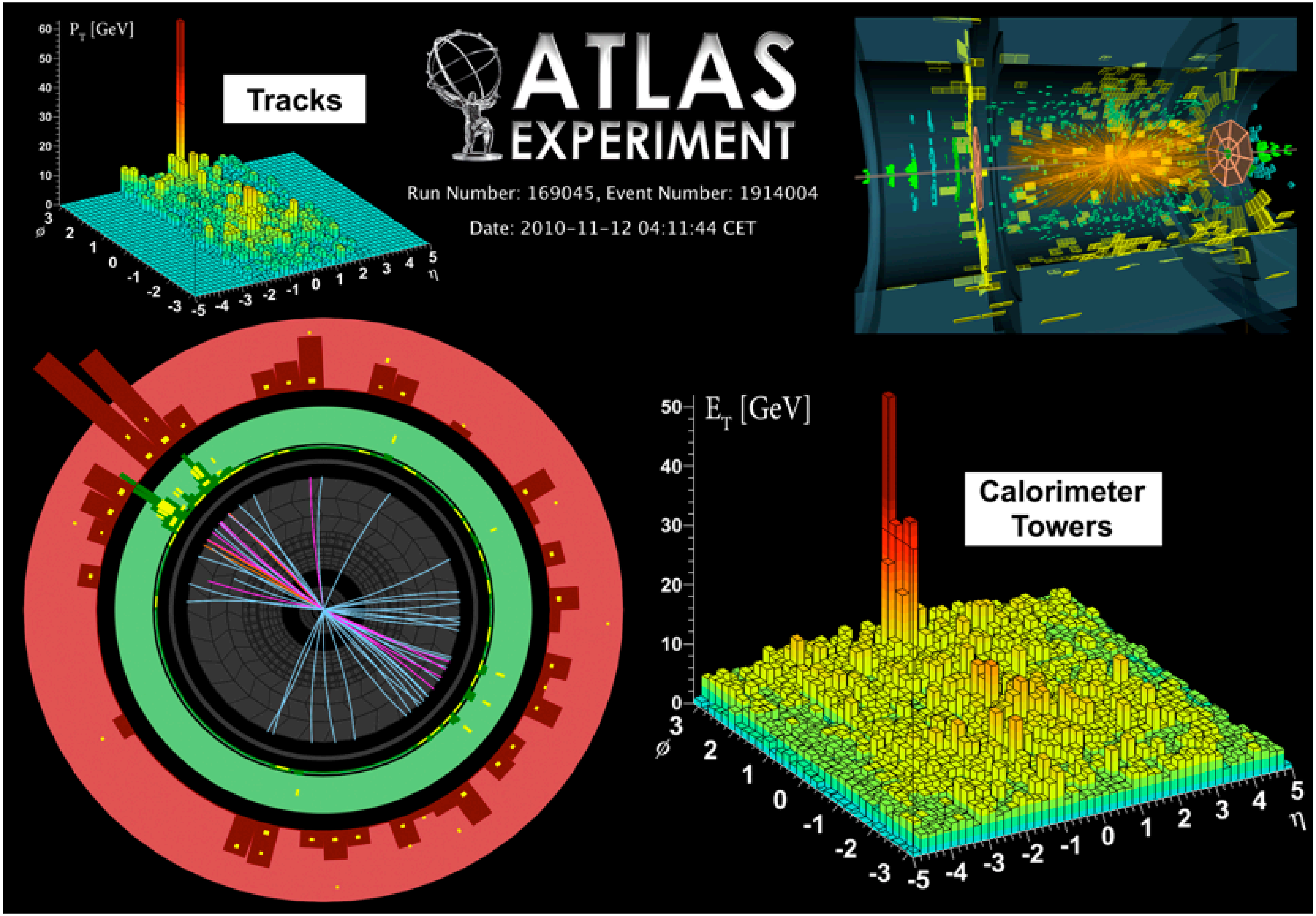
After UE subtraction:



Peripheral, symmetric dijet event



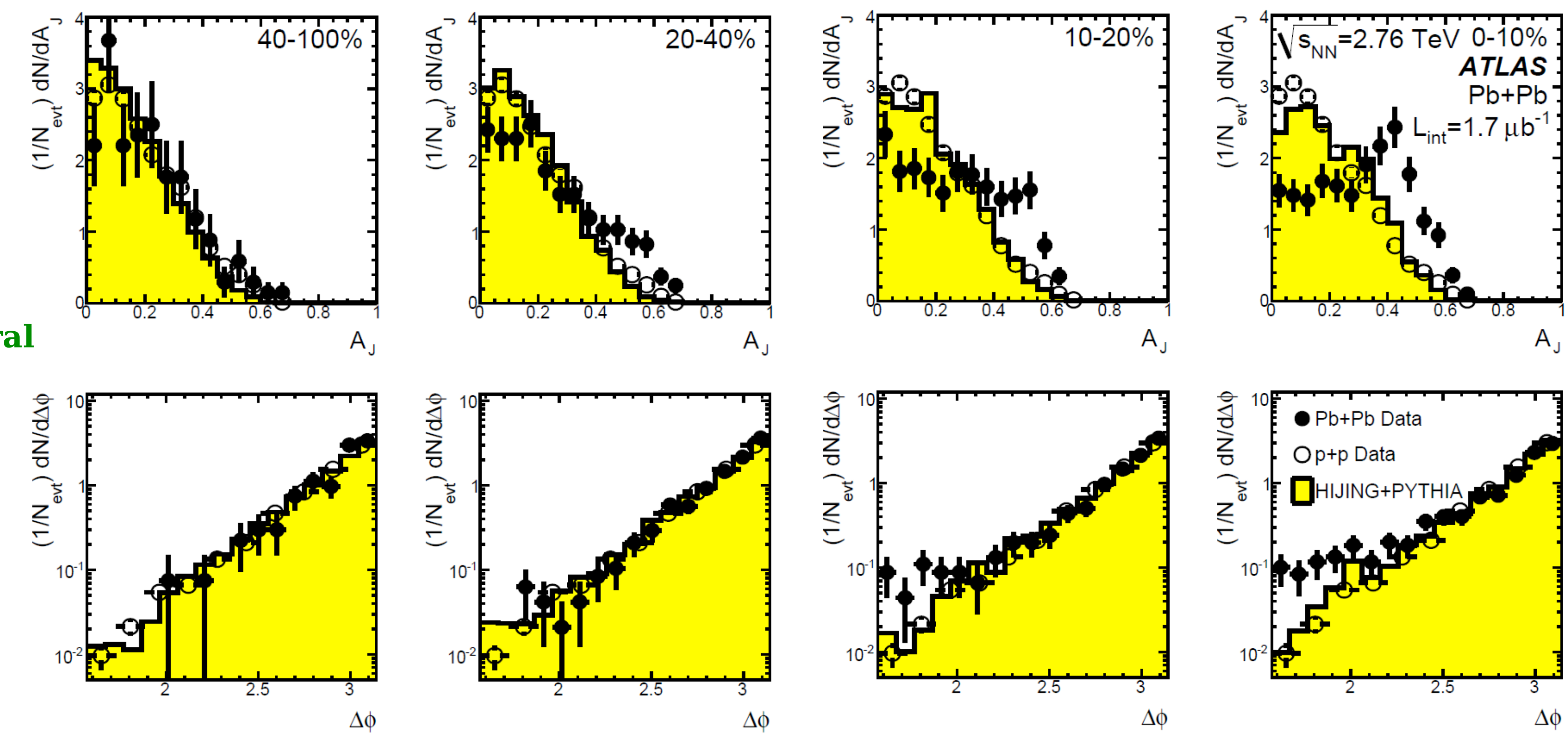
Central, *asymmetric* dijet event



Jet quenching at the LHC

- Asymmetry $A_J = (E_{T,1} - E_{T,2}) / (E_{T,1} + E_{T,2})$
  - Compare Pb+Pb data to *pp* data and HIJING Monte Carlo (with PYTHIA dijets overlaid)
- **Dijet asymmetry observed that increases with centrality**
  - Most symmetric in peripheral collisions, where pp behavior is recovered (left)
  - But very *asymmetric* in central collisions with largest nuclear overlap (right)

Peripheral



Central

Conclusions

- With ~45 pb^{-1} of data, jet p_T ~ 1.3 TeV and dijet mass ~ 3.7 TeV have already been observed and surpass the Tevatron reach
- First cross-section measurements of inclusive jet and dijet production at sqrt(s) = 7 TeV using 17 nb^{-1} (accepted by Eur. Phys. J. C)
  - First measurements at hadron collider using anti-k_T algorithm
  - Monte Carlo based calibration scheme was developed to calibrate jets as a function of p_T and y
    - JES uncertainty of 7% for central jets above 60 GeV
- New limit on dijet resonance mass: 0.87 TeV -> 1.26 TeV (published in PRL)
- New limit on contact interaction scale: 3.1 TeV -> 3.4 TeV (accepted by Phys. Lett. B)
  - QCD probed in new kinematic regime of high jet pT and large dijet mass
- First observation of jet quenching at sqrt(s_NN) = 2.76 TeV (published in PRL)

Outlook

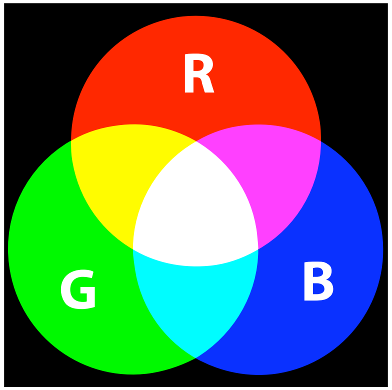
- ATLAS jet measurements and searches will have exciting new results for the Winter 2011 conferences
  - The full 2010 dataset of 45 pb^{-1} is being analyzed and will further extend the kinematic reach in both jet p_T and rapidity, and in dijet mass
  - Significantly reduced JES uncertainty using in-situ calibration methods is expected to be finished soon
  - Luminosity uncertainty will also be reduced
  - Other QCD analyses on dijets, multi-jets, jet shapes, etc have produced conference notes and are advancing towards publication
- Next year promises to be even more exciting with 1 fb^{-1} or more of data
  - Steve Myers has optimistically suggested that 2-5 fb^{-1} may be possible, so the future for jet measurements at the LHC is very bright!

Acknowledgments

ADDITIONAL MATERIAL

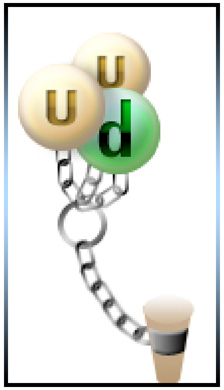
Quantum *chromo*dynamics (QCD)

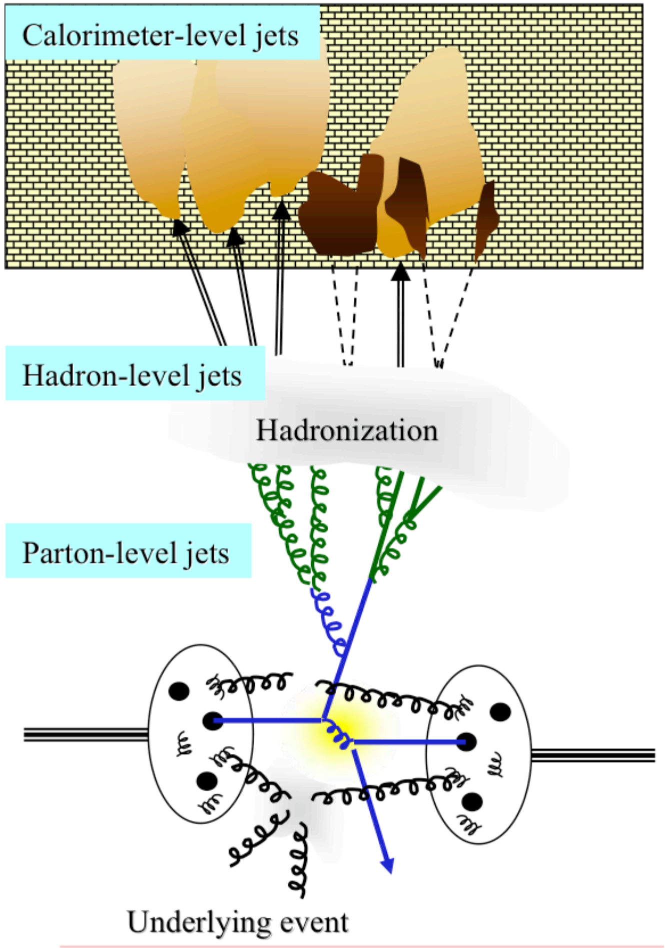
- Non-abelian gauge theory where:
  - Quarks have “color”, anti-quarks have “anti-color”
  - Gluons have both color and anti-color
  - Hadrons (bound states of quarks) are color neutral



Complications with QCD

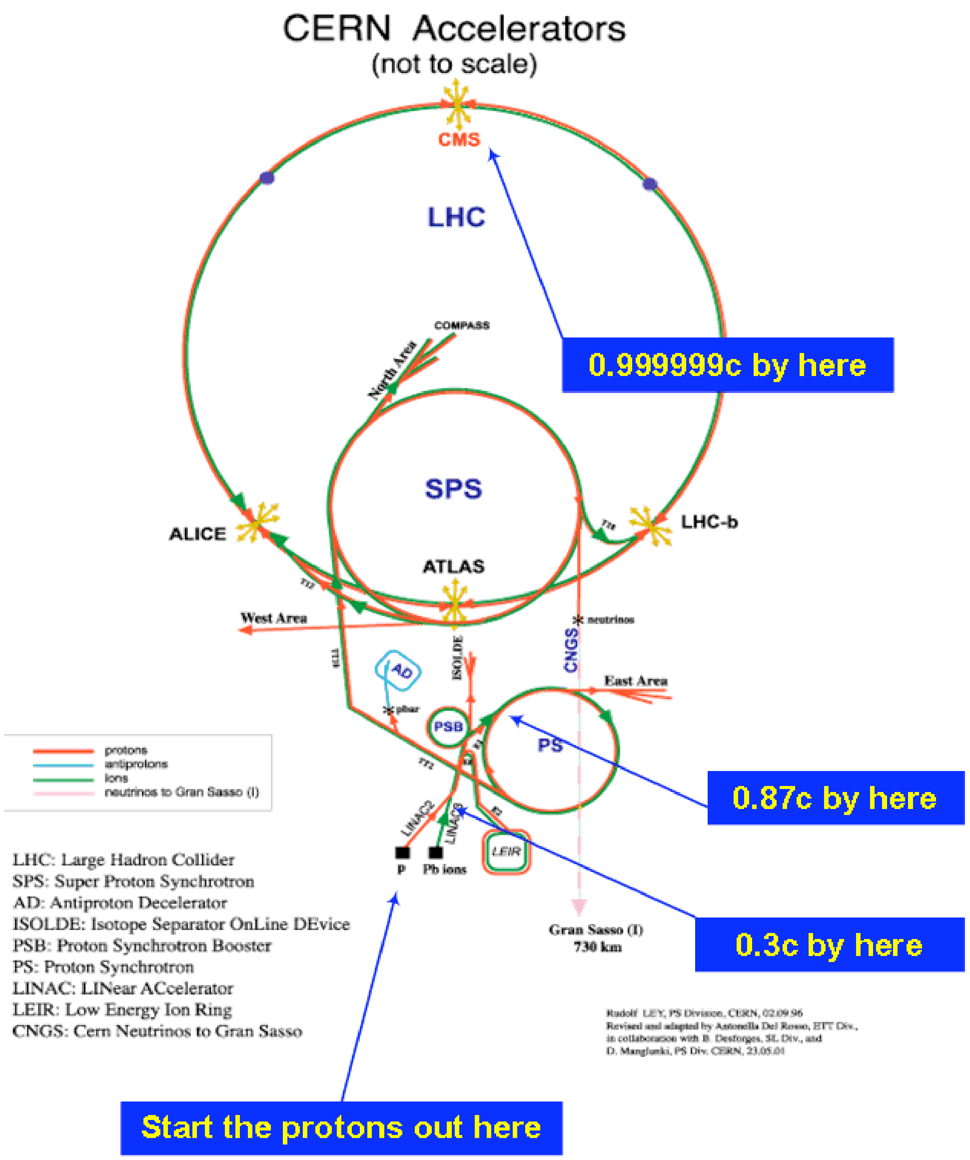
- So what's the difficulty?
- Asymptotic freedom → Partons behave as if free at large Q^2 i.e. very short distances
- But QCD becomes non-perturbative at low Q^2 (long distances)
  - Quark confinement
  - We measure jets (collimated flows of hadrons), not partons





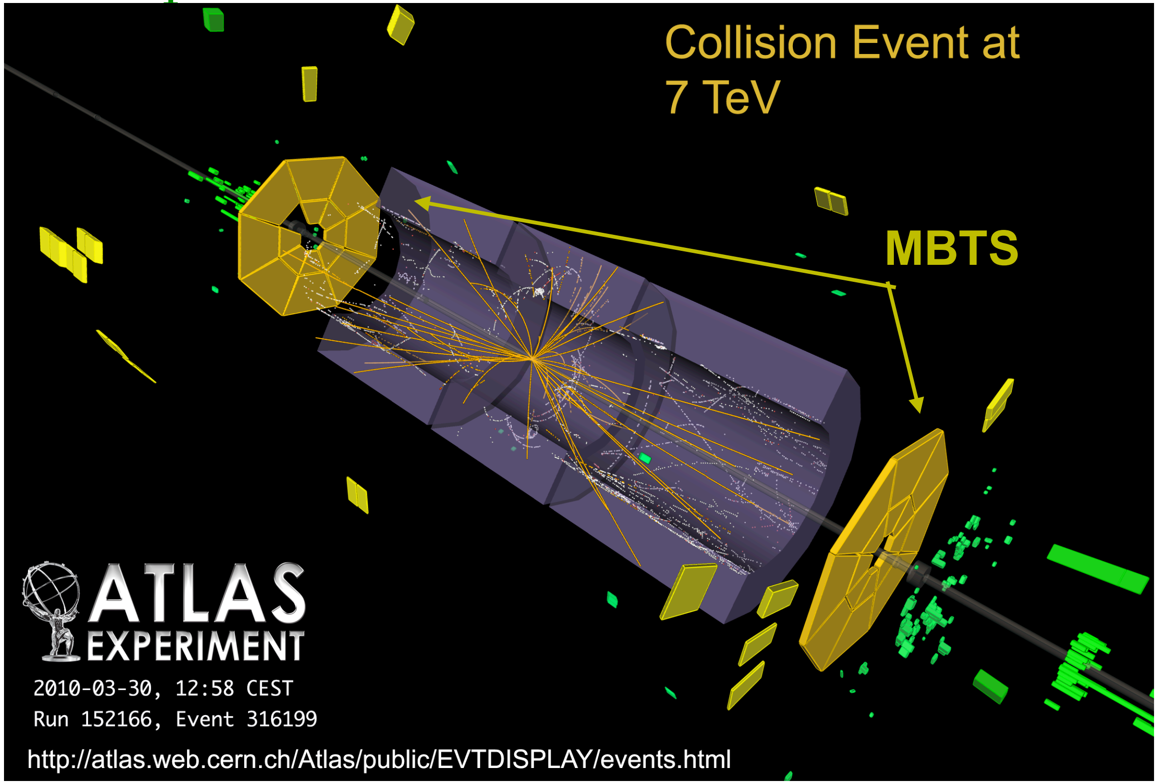
- This talk discusses how we have performed jet measurements in the ATLAS experiment and used these to probe *partonic* predictions of NLO pQCD, as well as to search for **new physics**

LHC accelerator complex



MBTS Trigger

- MBTS (Minimum Bias Trigger Scintillator) inclusive trigger
  - Require at least one scintillator fired from either η hemisphere: $2.09 < |\eta| < 3.84$
  - No significant bias introduced to the inclusive jet sample



Online and offline selection

- ***Only summarize briefly below due to time constraints – MUCH more detail in backup slides!***
- Data sample studied is between 17 – 300 nb^{-1} of data at 7 TeV collected through Period D before ICHEP
- Official Jet/EtMiss Good Run Lists and require "green" flag for luminosity
- Events with at least one "bad" (noisy) jet with p_T >10 GeV at EM scale are removed
- Require at least one vertex reconstructed within $|z|<10$cm of detector center to suppress beam halo and beam gas
- Require L1_J5 trigger fired from L1Calo stream
  - Restrict leading (sub-leading) jet to p_T>60 GeV (30 GeV) so that jet trigger and reconstruction are both fully efficient

What is the anti-k_T jet algorithm?

- Cone jet algorithms (sum all energy in some region)
  - ATLAS Cone (seeded → not infrared nor collinear safe)
  - SIS-Cone (Seedless Infrared Safe)
- Clustering AKA "sequential recombination" jet algorithms (invert the radiation and fragmentation)

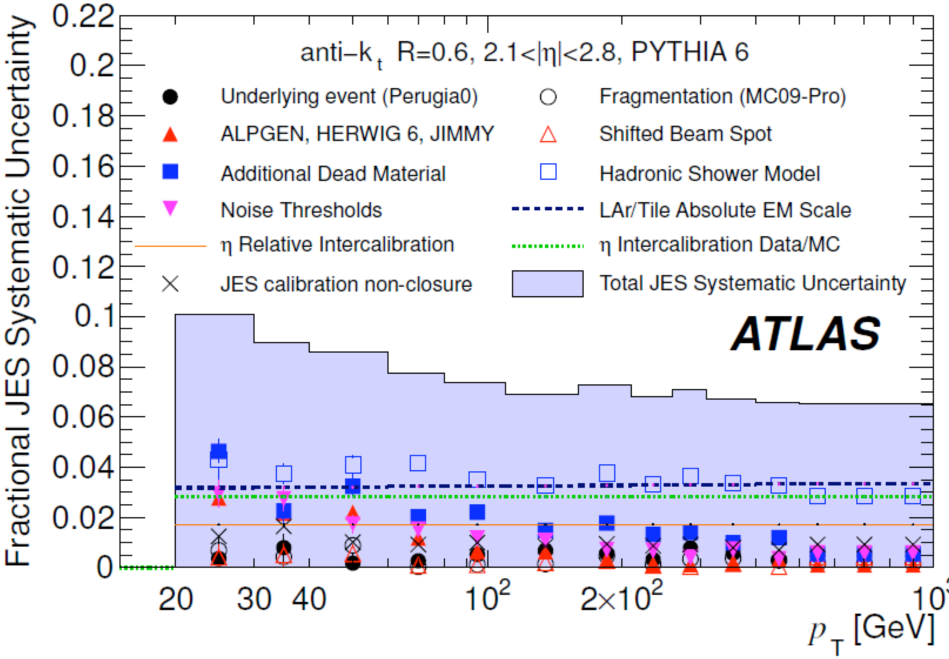
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \qquad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

  - K_T (p= 1): Clusters softest constituents first
  - Cambridge (p= 0): Clusters closest constituents first
  - Anti-k_T (p=-1): Clusters hardest constituents first

→ Reconstructs the same jets no matter whether there's soft radiation near the initial constituents

Absolute JES uncertainty

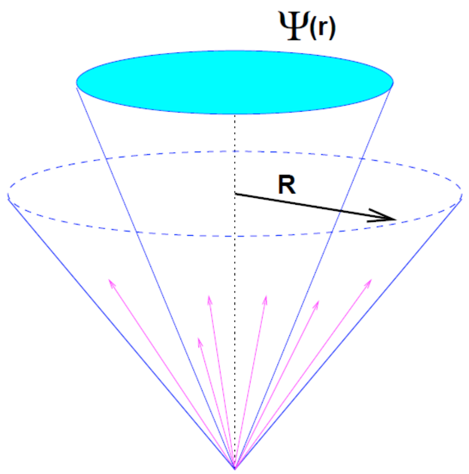
- Absolute JES uncertainty is slightly larger for forward jets and significantly bigger at lower jet p_T
  - Up to 10% at p_T = 20 GeV
- Dominant sources:
  - LAr/Tile EM scale: 3%
  - Hadronic shower: ~2-4%
  - Cluster noise thresholds
  - Material description
  - η intercalibration
  - Physics: Alpgen vs. Pythia

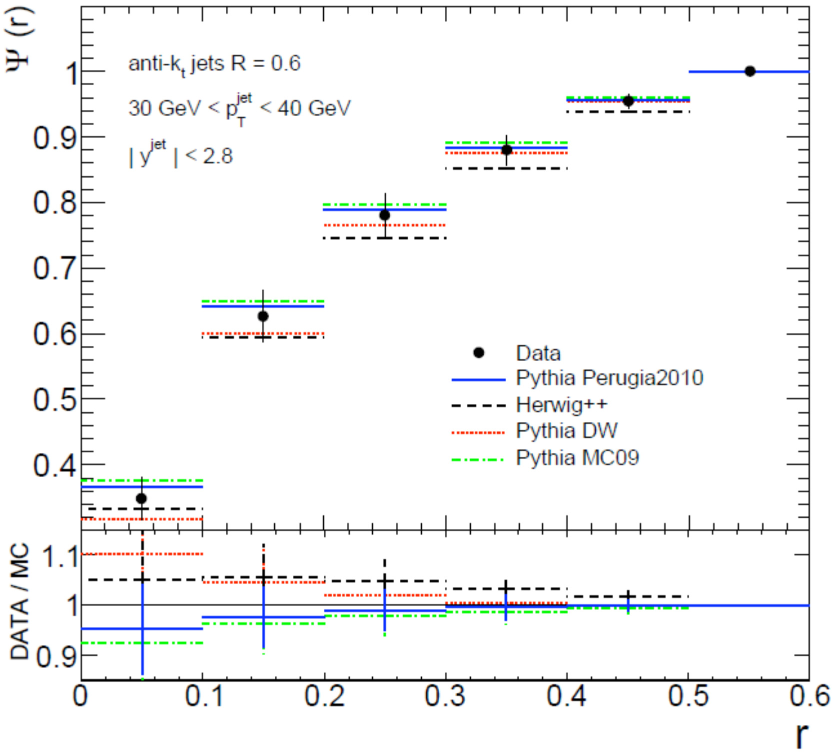


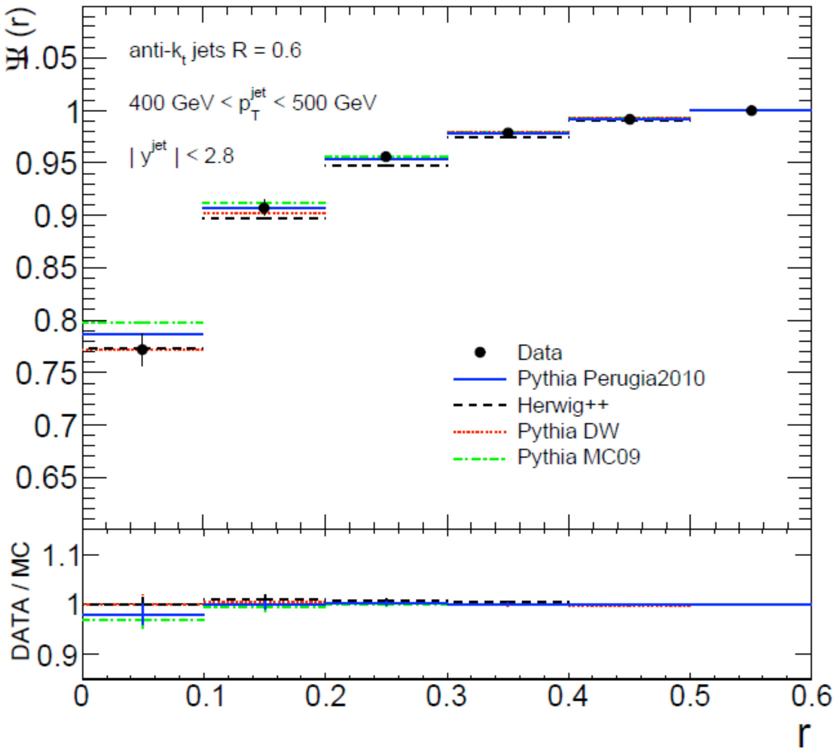
- ATLAS Collaboration. "Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy with the ATLAS detector." arXiv:1009.5908 [hep-ex]. Accepted by Eur. Phys. J. C.

Integral jet shape method

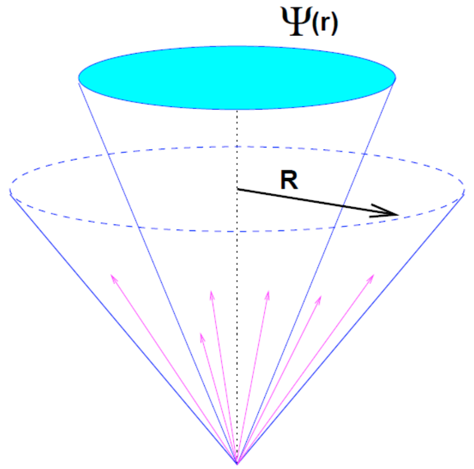
- Integral jet shapes can be computed as integral of the differential jet shape from the jet axis out to some radius R
  - Dominated by transverse momentum near jet axis







Integral jet shape



- Integral jet shapes Ψ(r) can be computed as integral of the differential jet shape from the jet axis out to some radius R
  - Dominated by measurement nearest to jet axis
- Thus 1 – Ψ(r=0.3) is the fraction of transverse momentum outside of r=0.3
- May eventually be useful to separate gluon and quark jets

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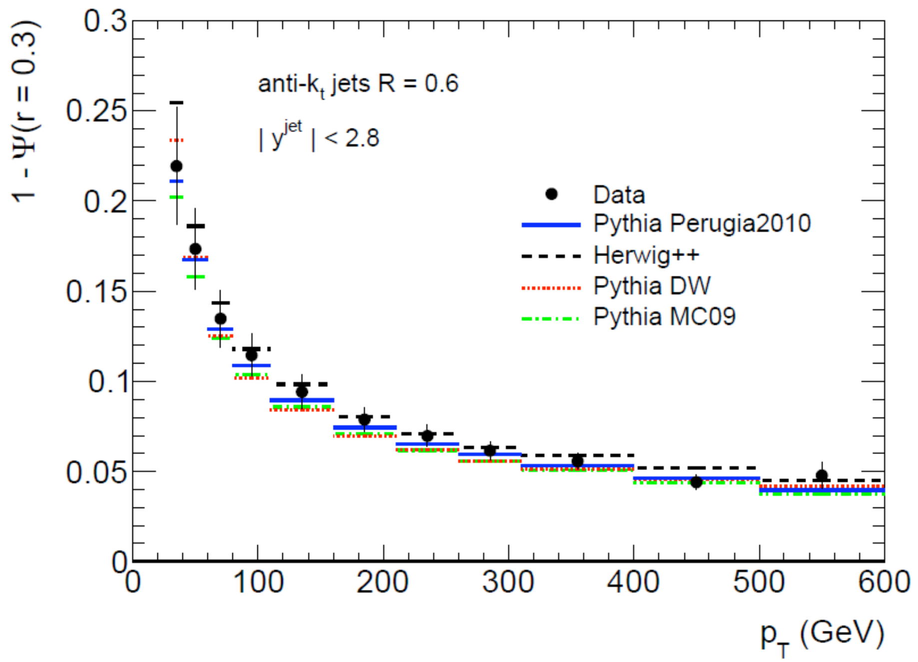
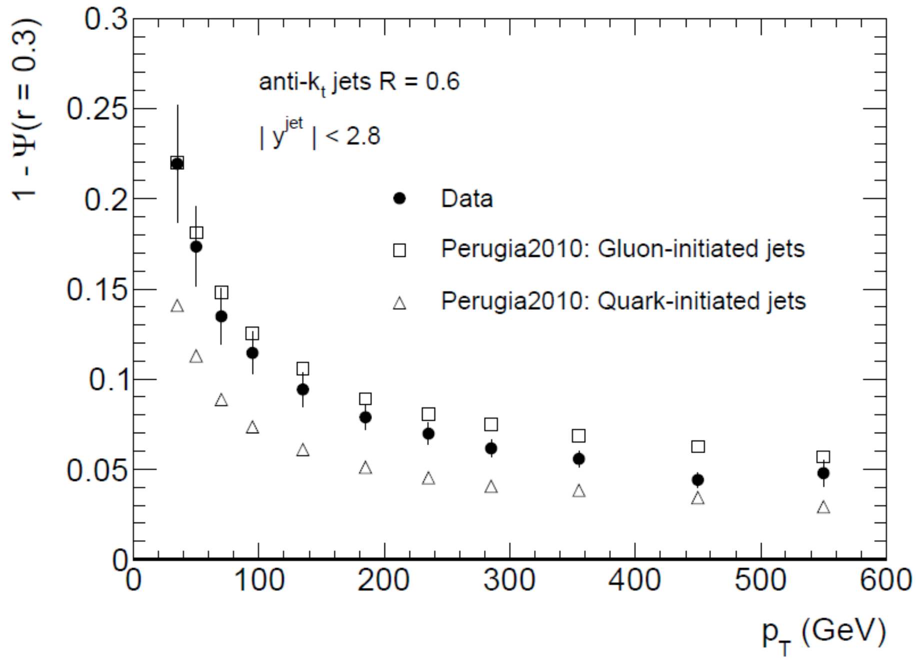




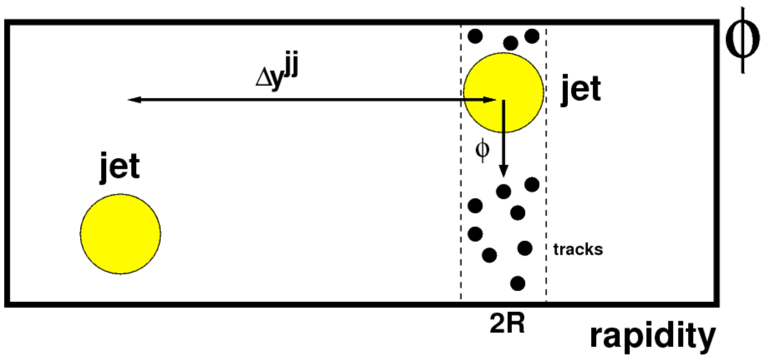
Charged particle flow: Method

- Charged particle flow in inclusive dijet events:

$$< \frac{d^2 p_T}{|d\phi| dy} >_{jets} = \frac{1}{2R|\Delta\phi|} \frac{1}{N^{jet}} \sum_{jets} p_T(|\phi - \Delta\phi/2|, |\phi + \Delta\phi/2|), \text{with } 0 \leq |\phi| \leq \pi$$

is the average transverse momentum as a function of the azimuthal distance from the jet axis and rapidity separation between the two leading jets

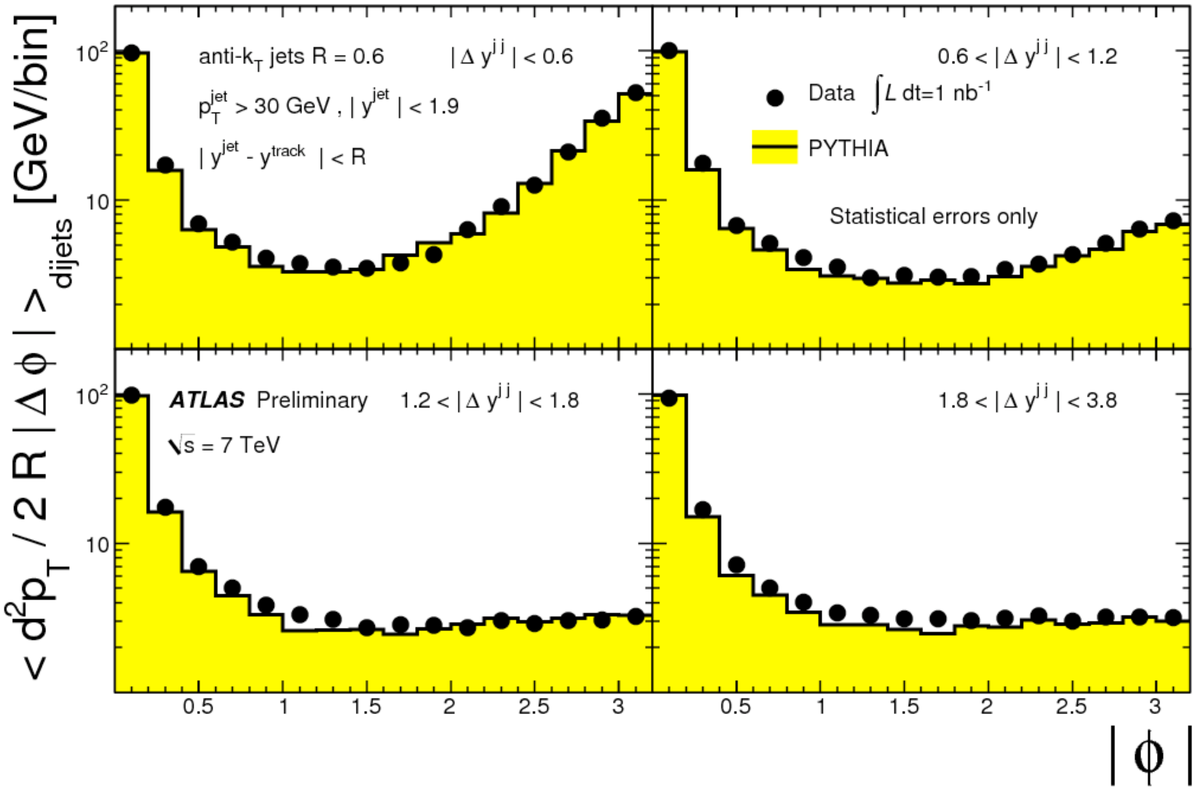
- Here p_T is computed as the scalar sum of the transverse momenta of tracks at a given angle φ with respect to jet axis



- Only tracks within rapidity range occupied by jet are used
- Jet required to be within |y|<1.9 to ensure that jet is fully within tracker acceptance |y|<2.5
- Track-based method is useful to confirm results from calorimeter-based jet shapes

Charged particle flow: Data distributions

- For $|\Delta y^{ij}| < 0.6$, two collimated flows of charged particles (dijets) observed at $|\varphi|=0$ and $|\varphi|=\pi$
- For $|\Delta y^{ij}|>1.2$, jet structure observed at low $|\varphi|$ followed by plateau of remaining hadronic activity as $|\varphi|$ increases
- Monte Carlo provides reasonable description of data, but slightly underestimates hadronic activity away from the jet direction (see backup)



Resolutions of jet observables

- Jet energy and angular resolutions studied in Monte Carlo in order to assign appropriate bin widths

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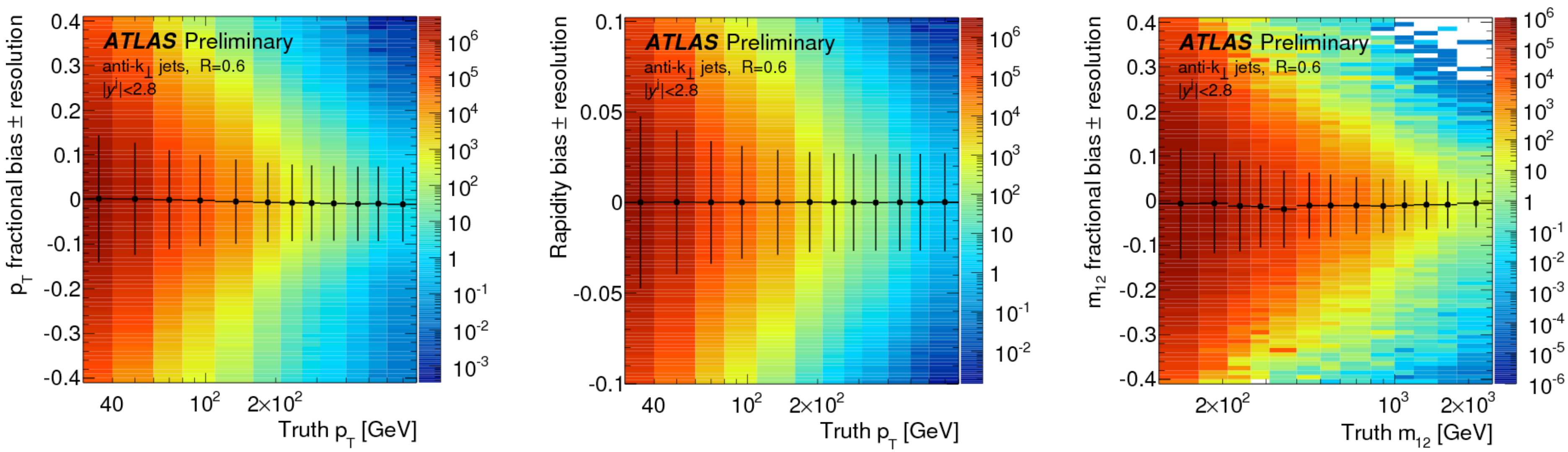

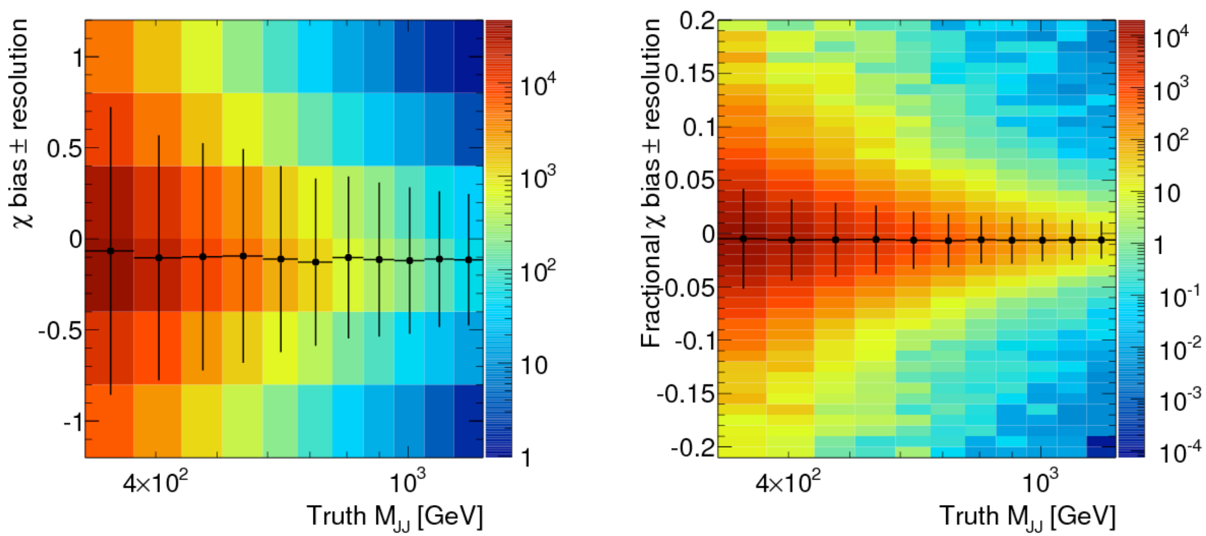

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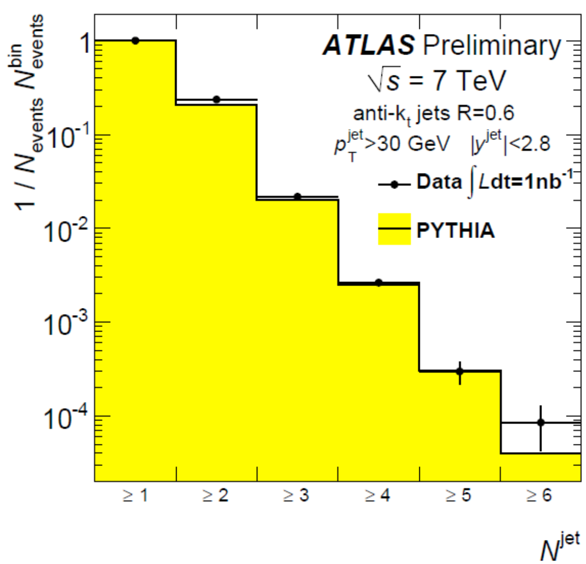
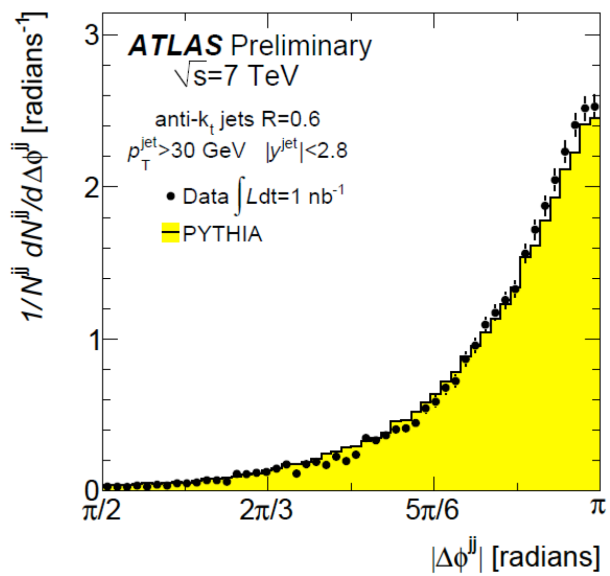
Jet observation at sqrt(s) = 7 TeV

- With 1 nb^{-1}, reported observation of jets at center-of-mass energy of 7 TeV on behalf of Jet/EtMiss and Standard Model groups
- Measured inclusive jet pT spectrum, dijet mass spectrum, and dijet azimuthal decorrelation





- E. Feng (for the ATLAS Collaboration). "Observation of Energetic Jet Production in pp Collisions at sqrt(s) = 7 TeV using the ATLAS Experiment at the LHC." arXiv:1010.1974 [hep-ex]. To appear in *Proceedings of PLHC 2010*, Hamburg, Germany, June 2010.

Jet properties

Jet width and rapidity

- Studied inclusive jet, dijet, and multi-jet observables to test description of calorimeters, jets, and missing E_T in Monte Carlo
- Jet radial width shown to be wider in data than predicted by MC09
  - Consistent with jet shapes!
- Monte Carlo description was shown to be satisfactory for jets in |y|<2.8

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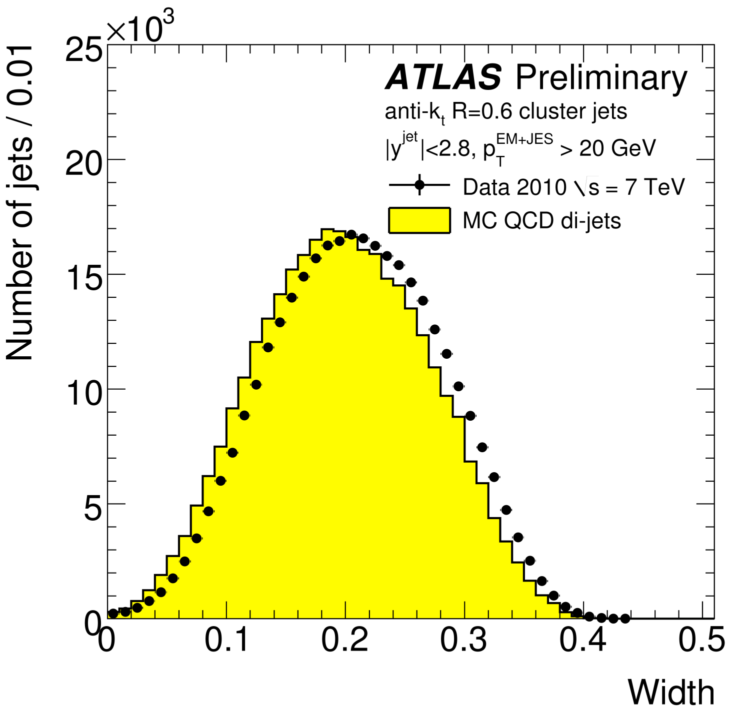

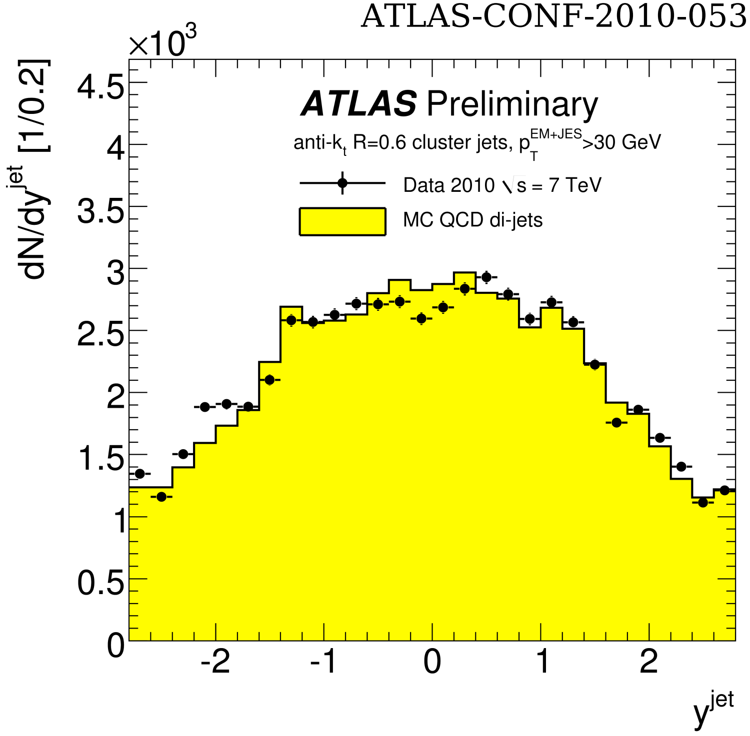

Jet energy in different calorimeter layers

- Detailed studies of jet energy deposited in each layer of calorimeter
- Second layer of EM and hadronic calorimeters shown below
  - Good agreement between data and MC

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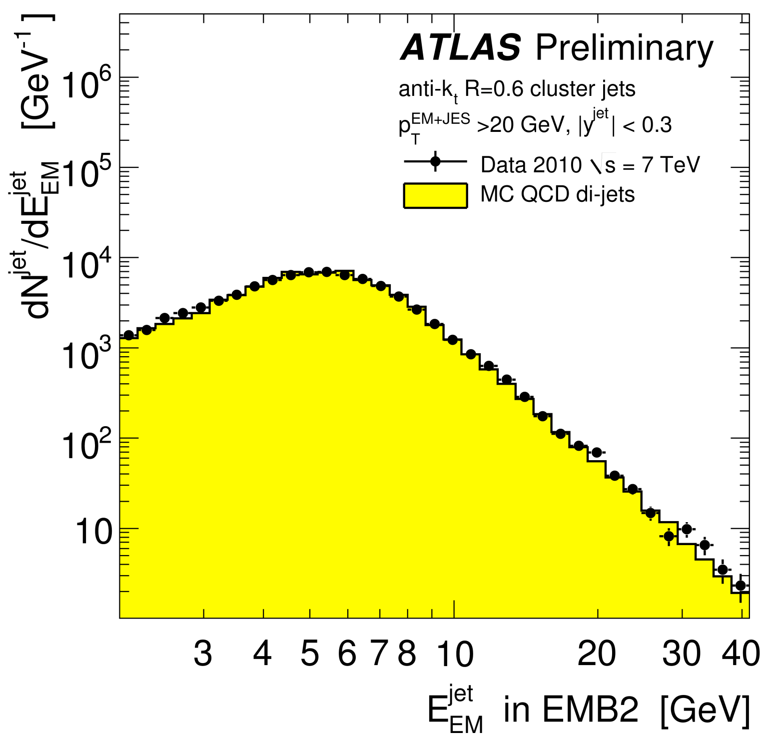

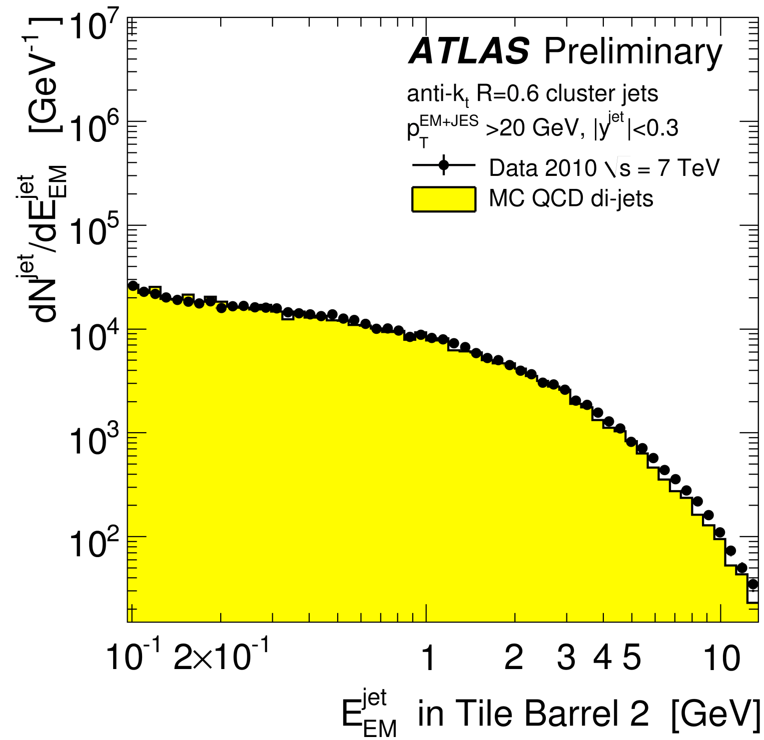

More tests of perturbative QCD

Dijet Azimuthal Decorrelation (Δφ)

- Dijet angular distribution: $\Delta\varphi = |\varphi_1 - \varphi_2|$ measured in bins of leading jet p_T
- Peak at $\Delta\varphi=\pi$ → dominant final state is back-to-back dijets
  - Deviation from $\Delta\varphi=\pi$ due to radiation of one or more gluons
  - 3-jet final state calculated using NLO pQCD

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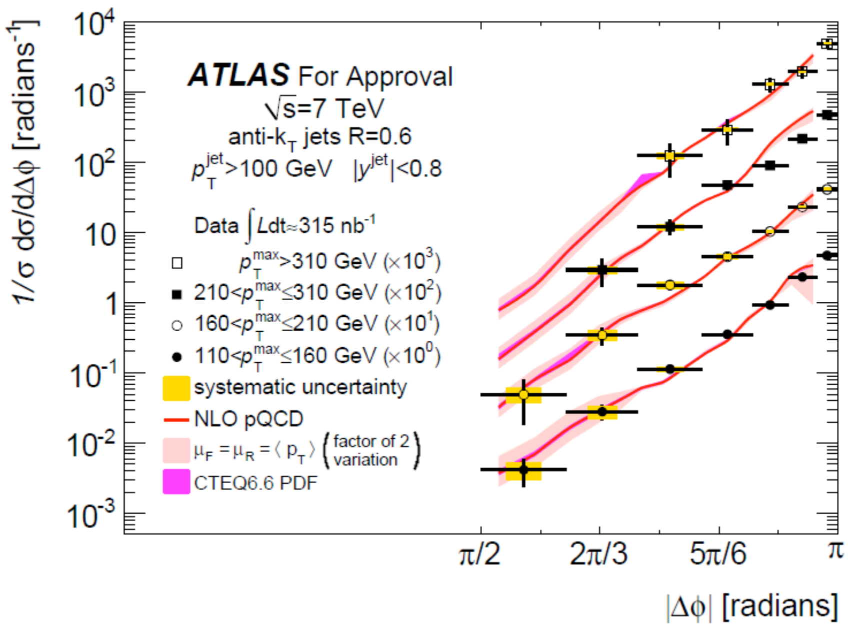

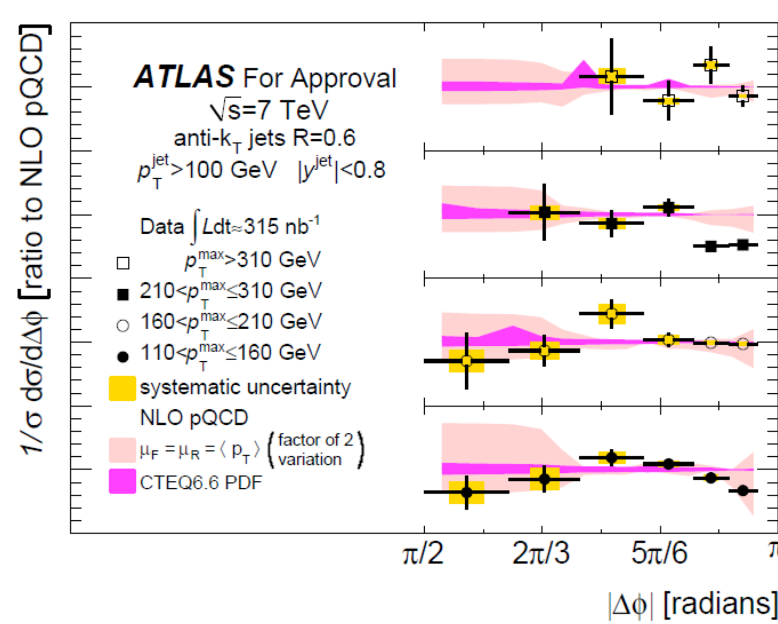

Dijet Azimuthal Decorrelation (Δφ)

- Four or more real emissions is best modeled using a leading-order ME generator with 2->N matrix elements
  - Sensitive to different angular distributions produced by 2->2 vs. 2->N parton shower Monte Carlos
- Useful to tune amount of ISR/FSR and underlying event in parton shower Monte Carlo

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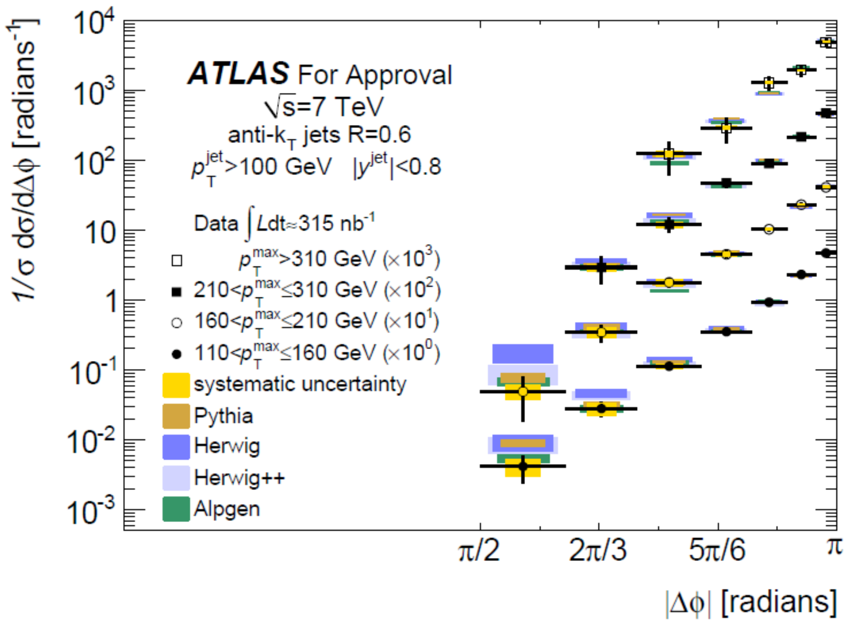

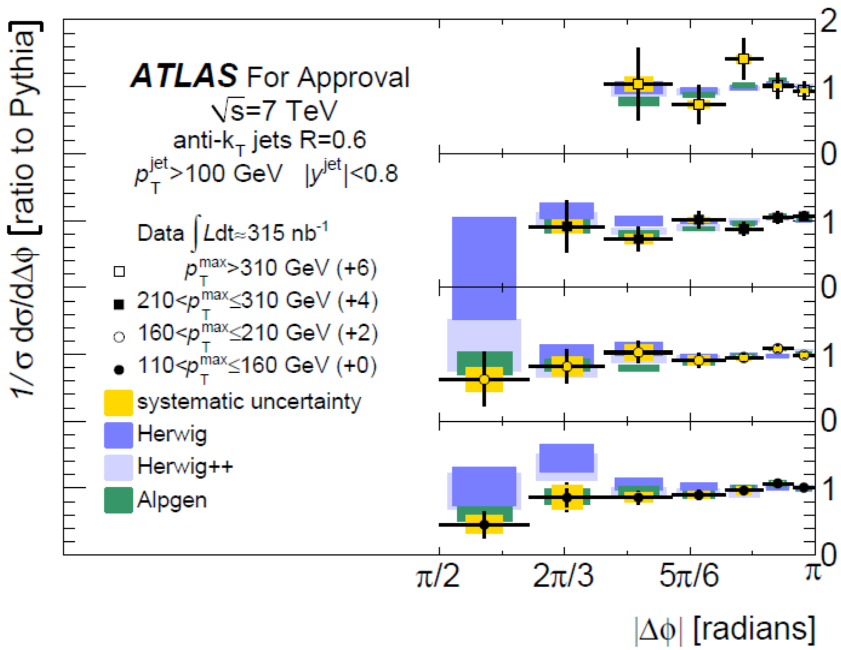

Dijets with Rapidity Gaps

- Measure fraction of events with gap between two boundary jets:
  - Two highest p_T jets (left), OR
  - Most forward and most backward jet (right)
- Sensitive to BFKL dynamics vs. DGLAP evolution
- Also can study wide-angle soft-gluon radiation
- Uses Monte-Carlo based JES uncertainty up to |y|<4.5

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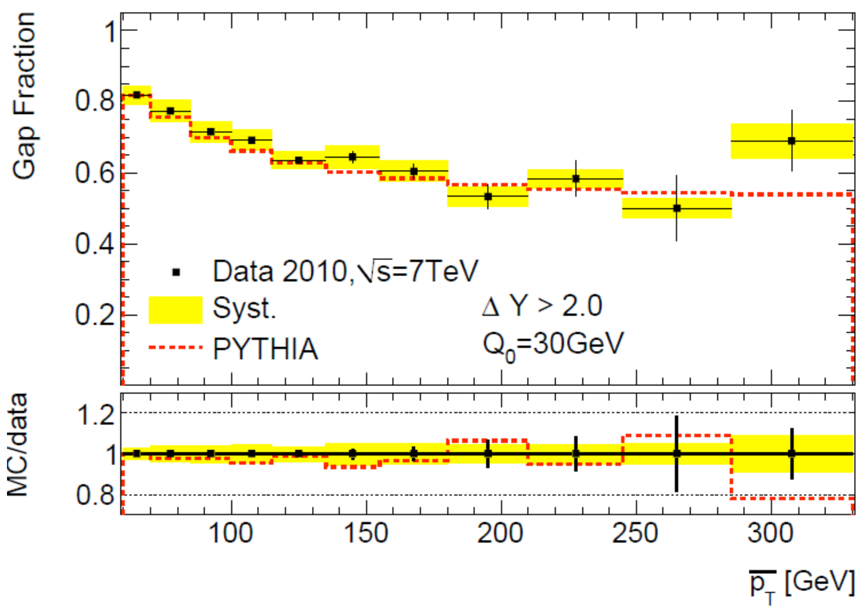

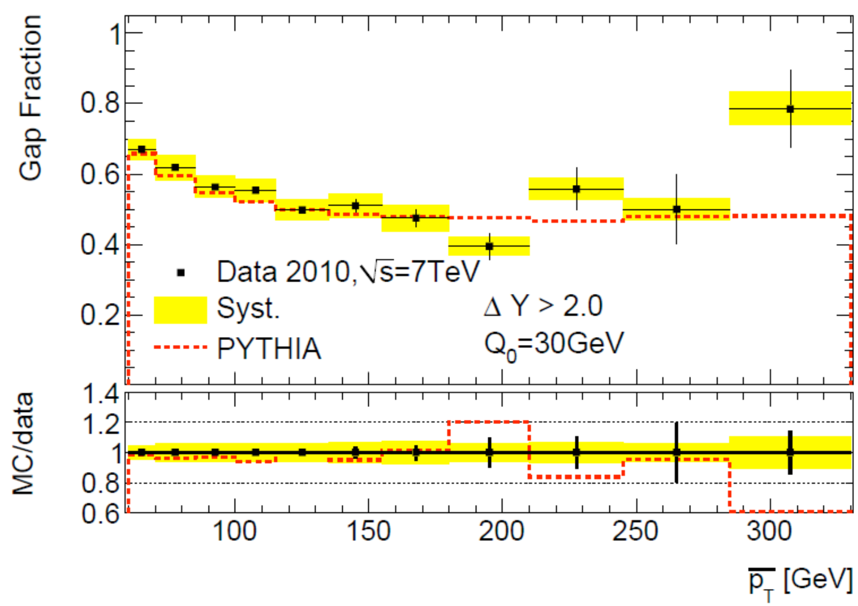

Multi-Jets: p_T-ordered cross-sections

- Subdivision of the inclusion jet cross-section into separate cross-sections for each of the p_T-ordered jets
- Sensitive to matrix element and final state radiation

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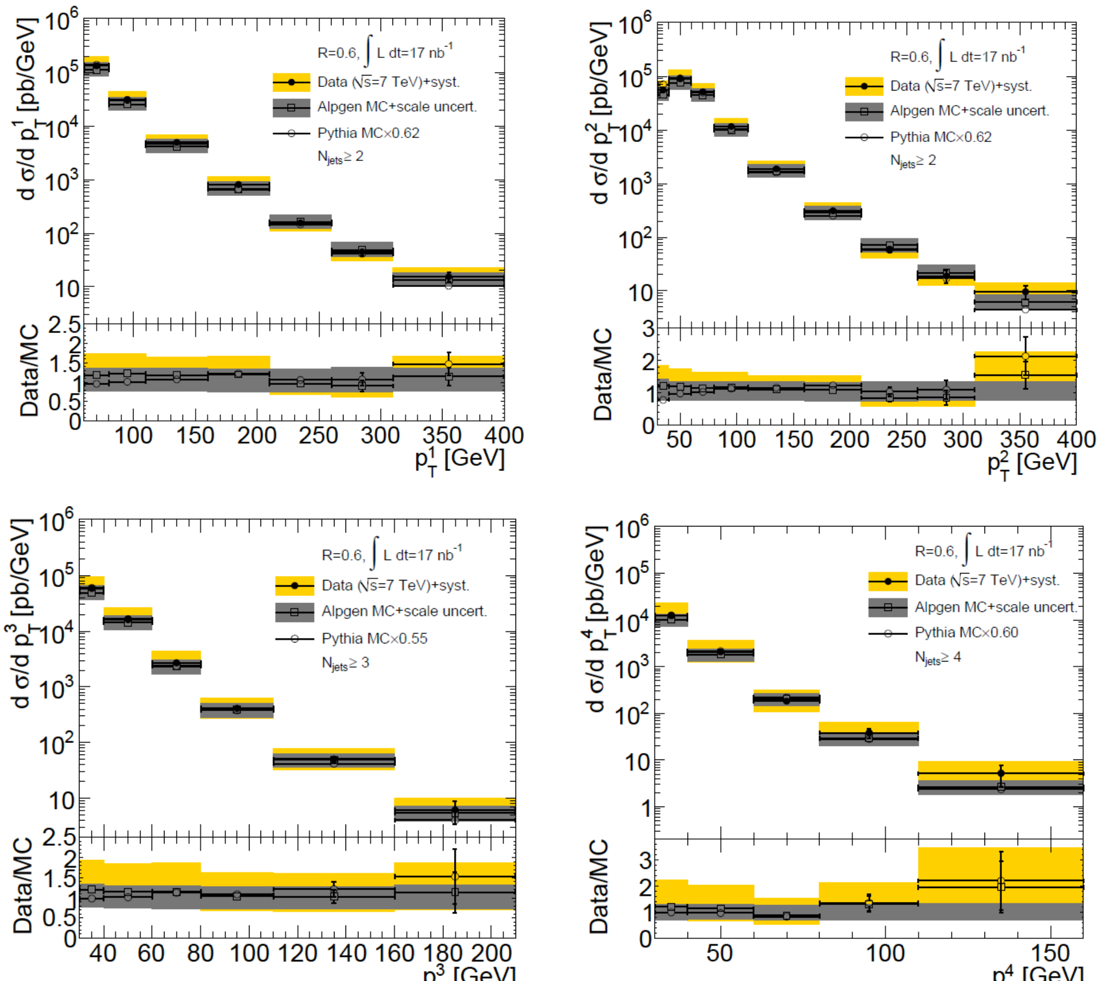

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Multi-Jets – H_T

- H_T = scalar sum of jet p_T
- Ratio of 3-jet and 2-jet cross-sections in H_T is a direct probe of α_S
- Additional uncertainty in absolute JES due to flavor (quark vs. gluon) as well as close-by jets has been studied

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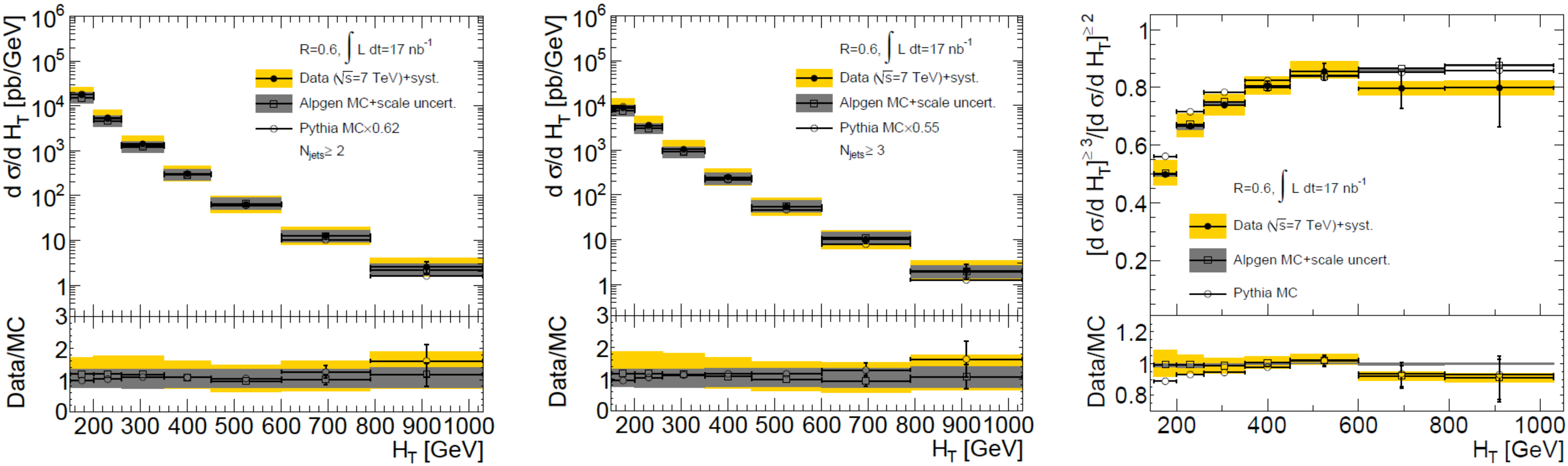


Even more QCD analyses

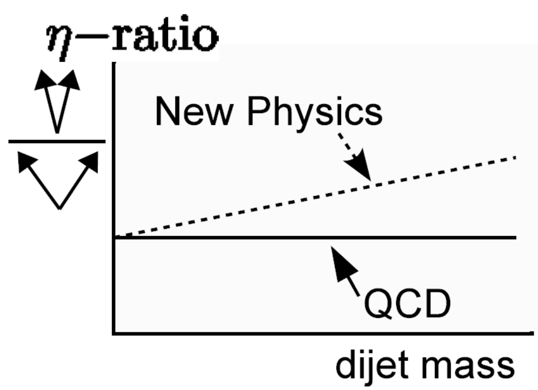
- Many more jet and QCD-related analyses finished or in progress
    - Inclusive jet cross-section measured using track-jets
    - Jet fragmentation measured using tracks
    - Vector boson production in association with jets (W/Z + jets)
    - Diffractive dijets
    - Etc...
- All of these analyses are very interesting, but unfortunately do not have time to describe them here...

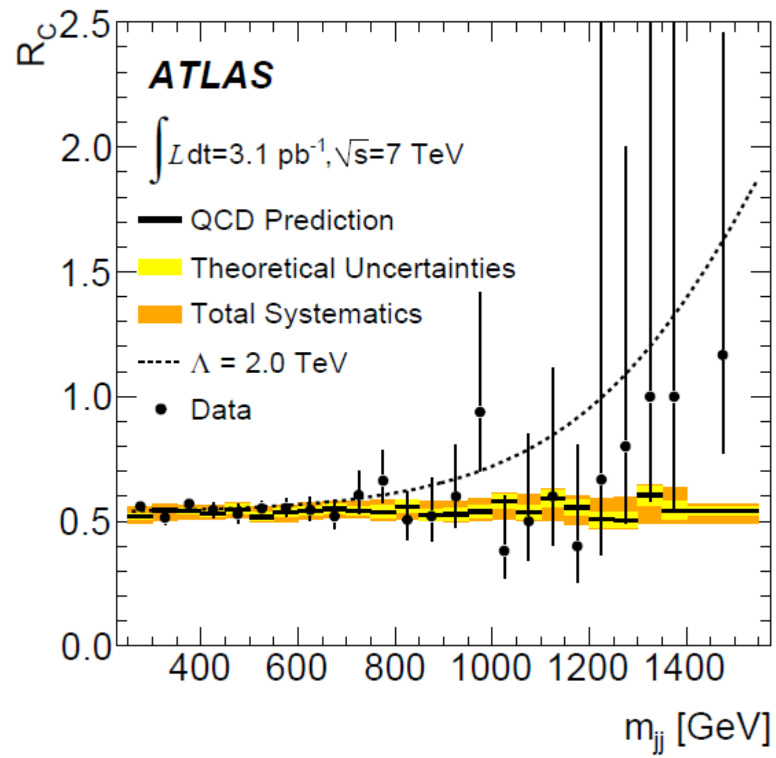
Search for contact interactions using the η ratio

- Checked ratio of large-opening to small-opening jets for tail as a function of dijet mass:

$$\eta\text{-ratio} = \frac{N(|\eta_{1,2}|<0.5)}{N(0.5<|\eta_{1,2}|<1)}$$

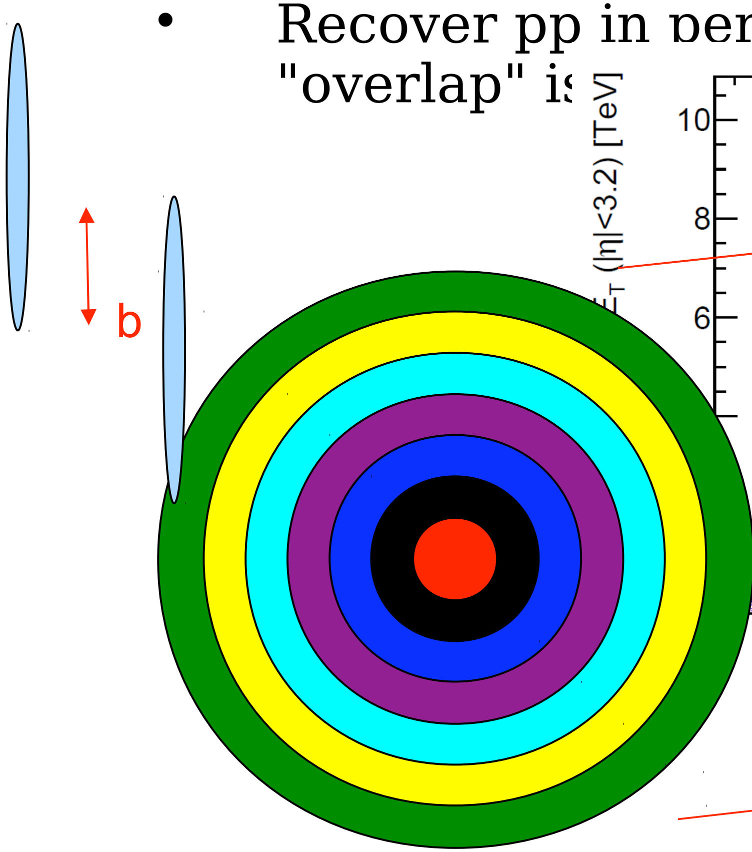
  - Like χ, largely cancels out JES uncertainty and leaves relative JES
  - Also sensitive to contact interactions from small-angle scattering

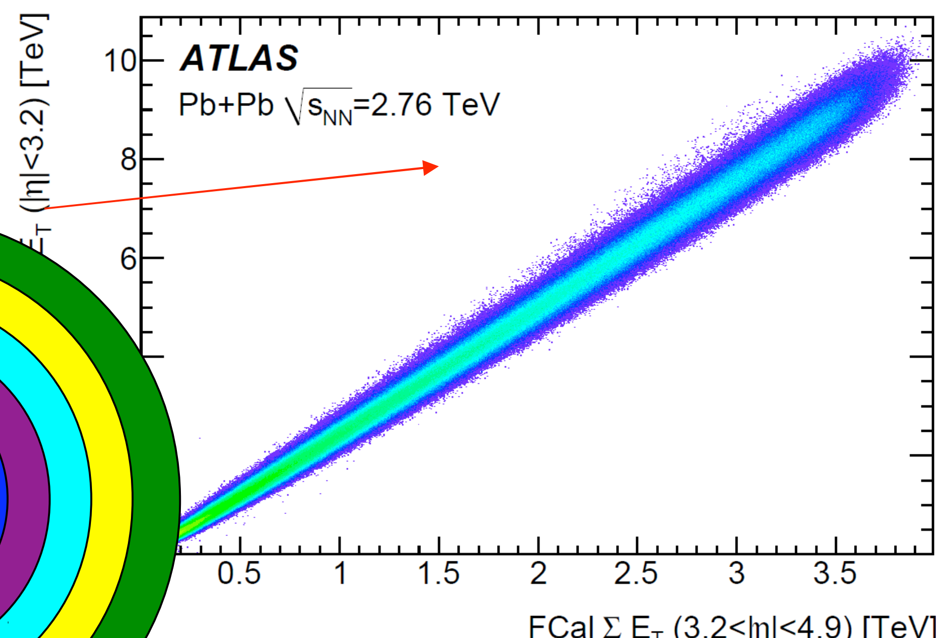


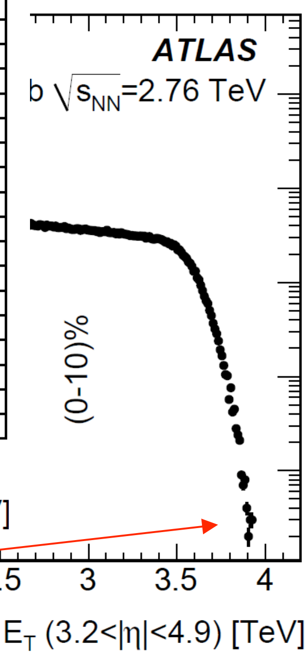


Centrality definition

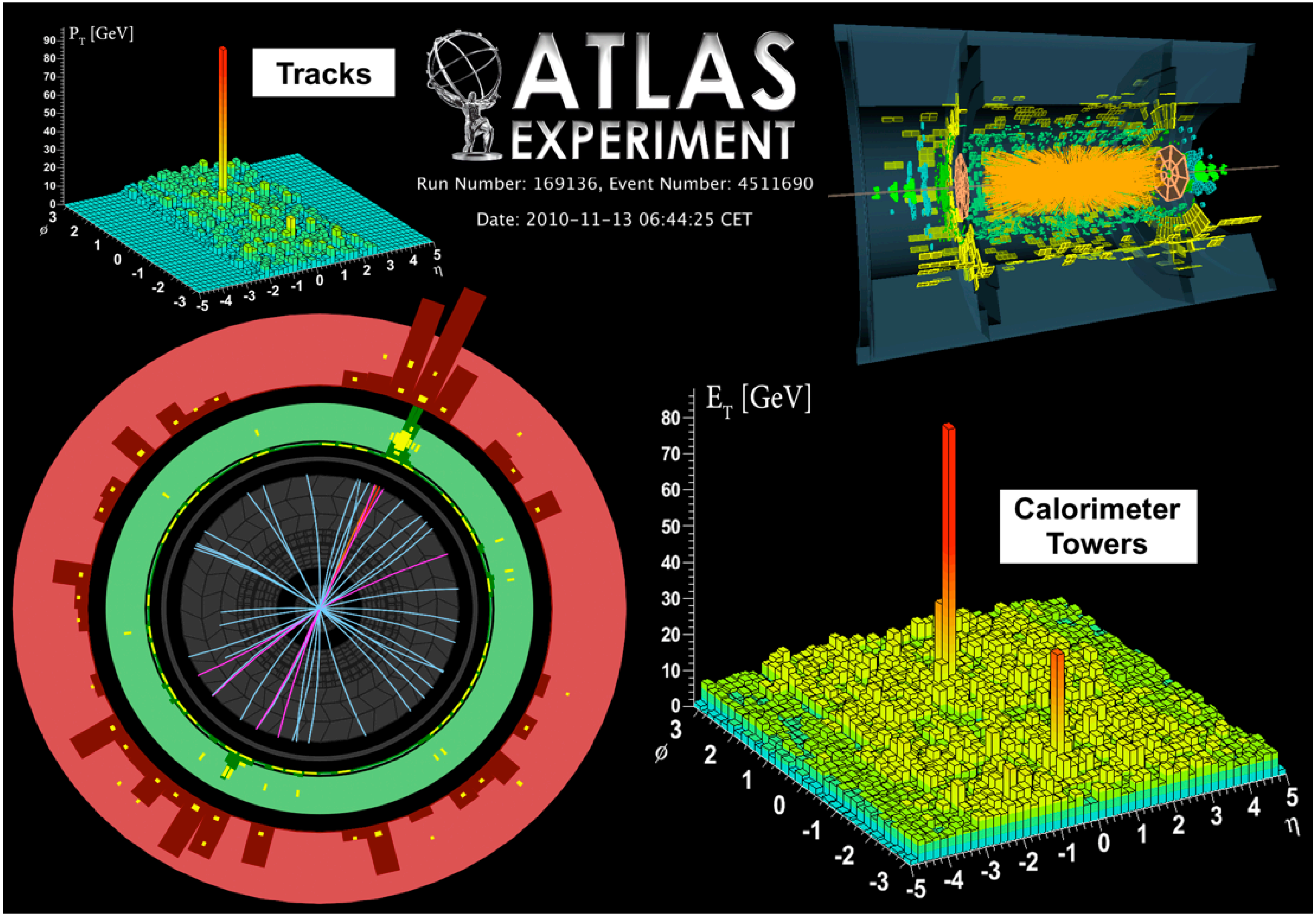
- Particle multiplicity increases as classical impact parameter b decreases
- Characterize centrality by percentiles of total cross-section using ΣE_T in Forward Calorimeter (Fcal) spanning $3.2 < |\eta < 4.9$
    - Recover pp in peripheral collisions where nuclear "overlap" i







More central, asymmetric dijet event



Central event, with split dijet and additional activity